High Lift OVERFLOW Analysis of the DLR F11 Wind Tunnel Model

Thomas H. Pulliam
NASA Ames Research Center
Moffett Field, California, USA

Anthony J. Sclafani
Boeing Research & Technology
Huntington Beach, California, USA

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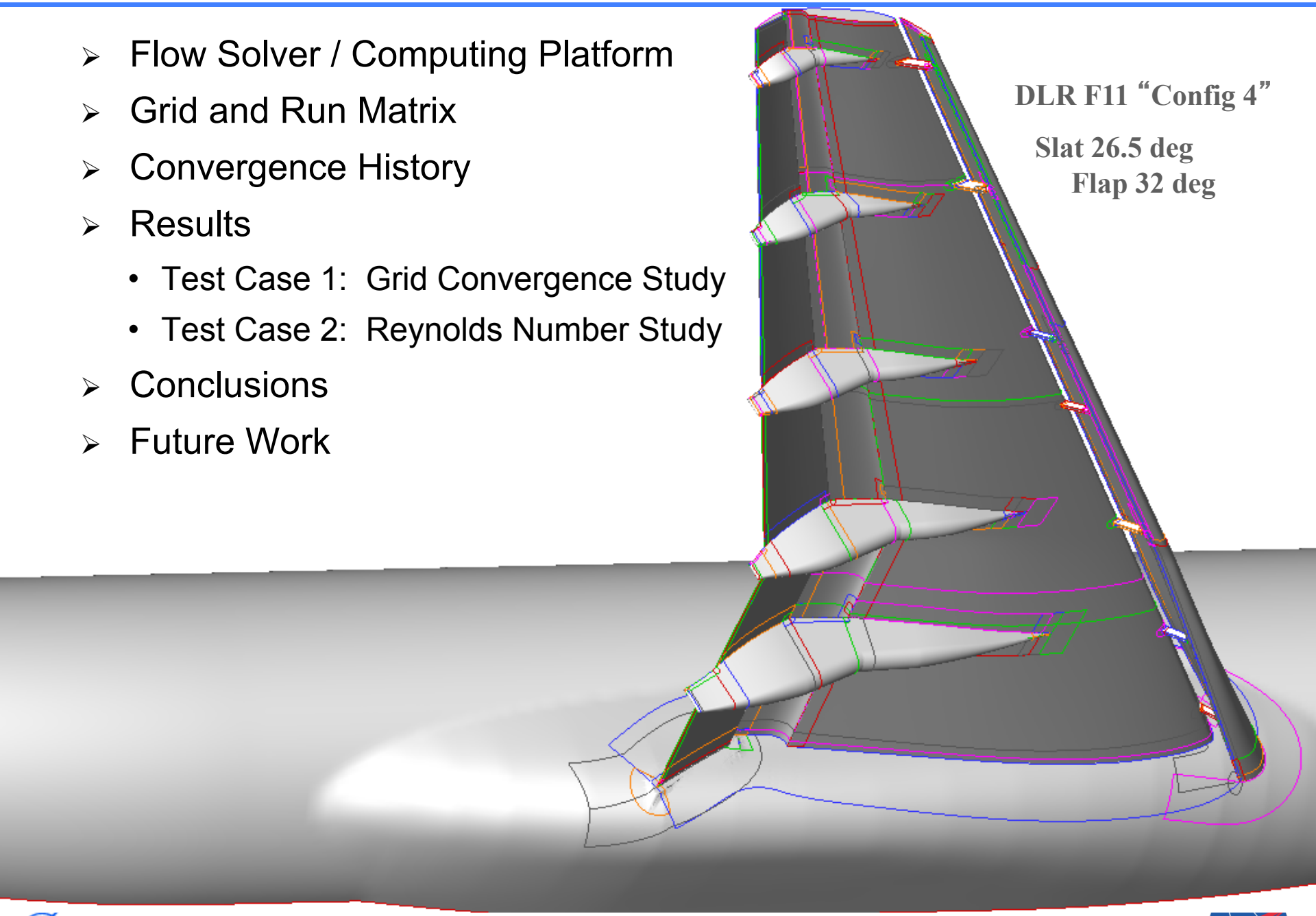
Outline

- Flow Solver / Computing Platform
- Grid and Run Matrix
- Convergence History
- Results
  - Test Case 1: Grid Convergence Study
  - Test Case 2: Reynolds Number Study
- Conclusions
- Future Work



Flow Solver / Computing Platform

OVERFLOW Version 2.2f

- Default Setup – Steady State, QCR off
  - 3rd order Roe upwind differencing
  - SA-RC turbulence model (SA-noft2 with rotation/curvature corrections)
  - full N-S, exact wall distance calculation, low Mach preconditioning
  - restart from lower α solution
  - fully turbulent boundary layer
- Additional Studies
  - linear vs. nonlinear stress model via QCR

Pleiades Supercomputer

- SGI ICE cluster with >100,000 cores
- Medium grid cases run on 256 cores with 4 OpenMP threads
  - 4.5 seconds per iteration, acceptable convergence reached after 20,000 iterations
  - Roughly 24 hours of wall clock time needed per case

Quadratic Constitutive Relation (QCR)

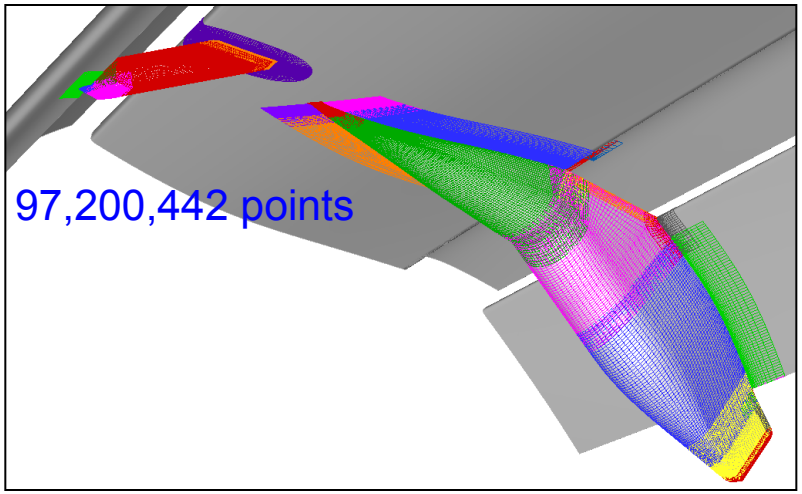
- *Approach published by P. Spalart*
- *Improve upon the linear eddy viscosity approximation by using a nonlinear stress term to model the Reynolds stresses directly*
- *Improves solution accuracy for corner flows compared to a linear (i.e., Boussinesq) eddy viscosity model*

Grid and Run Matrix

Config 2: Brackets/Fairings Off (44 zones)

	Grid	Points	$1/N^{2/3} \times 10^5$	
1-to-2	Coarse	29,386,628	1.050	4-to-3
	Medium	69,014,980	0.594	3-to-2
	Fine	230,770,520	0.266	4-to-3
	Extra-Fine	544,468,508	0.150	

Config 4: Brackets/Fairings On (163 zones)



OVERFLOW Run Matrix

	coarse	medium	fine	extra-fine
Case 1	A1, A2	A1, A2	A1, A2	A1
Case 2a		A1, A2		
Case 2b		A1, A2		

Black font = data submitted for workshop
Red font = data not submitted for workshop

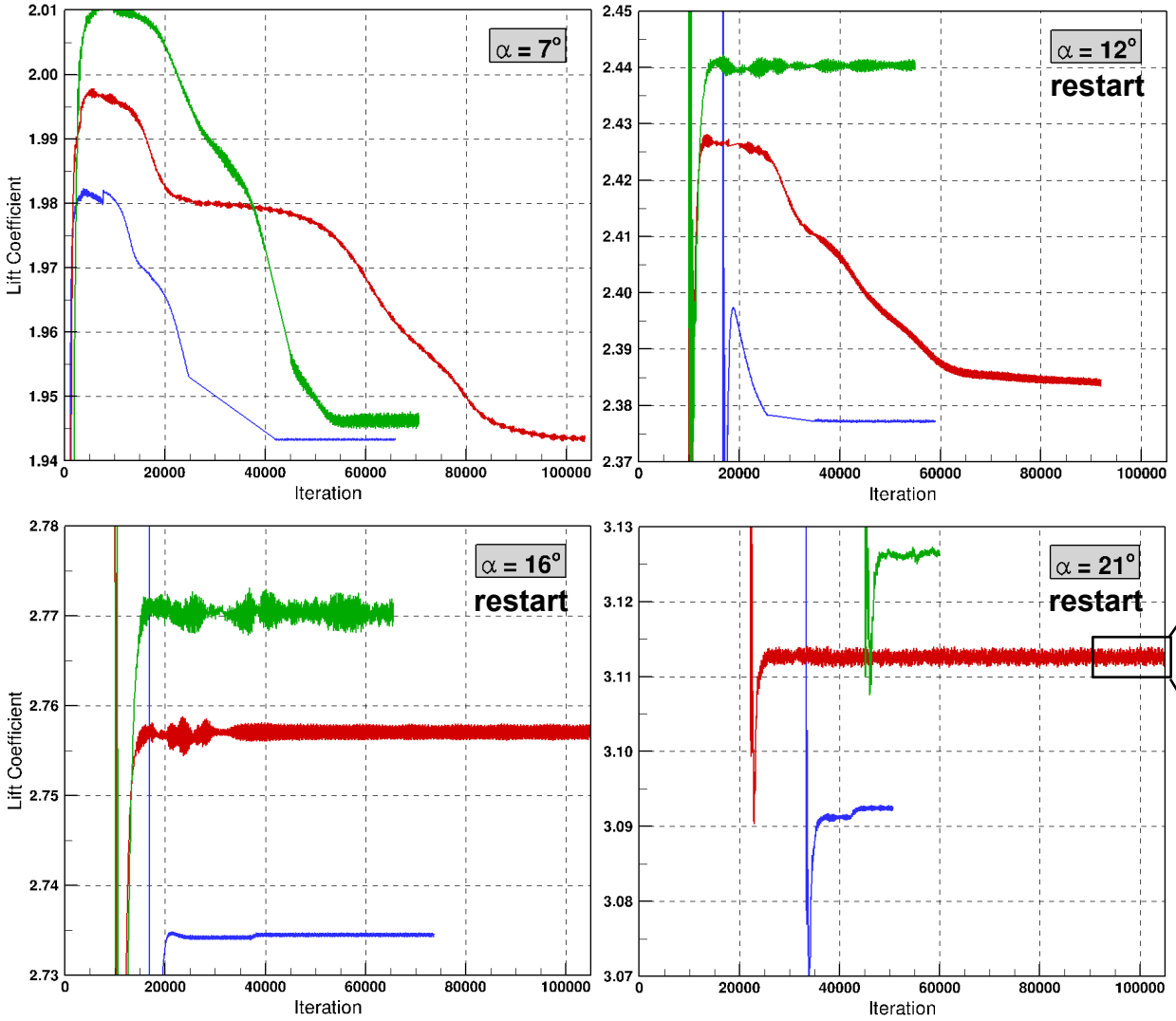
Analysis Type
A1 = Steady State, QCR off
A2 = Steady State, QCR on
A3 = Unsteady, QCR off
A4 = Unsteady, QCR on

Convergence History
Case 1 C_L – Grid Effect, QCR Off

F11 Config 2: Slat Brackets / Flap Fairings Off

Mach = 0.175, Reynolds number = 15.1 million

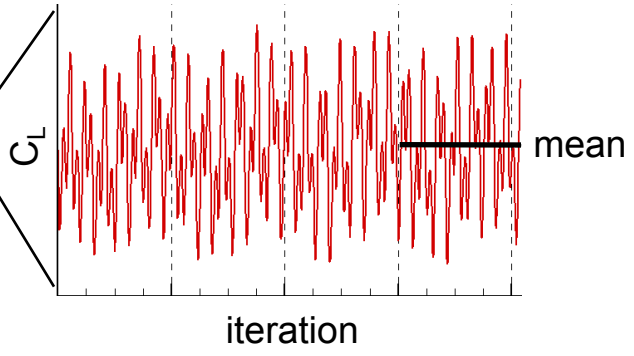
Fully Turbulent, Free Air



Coarse

Medium

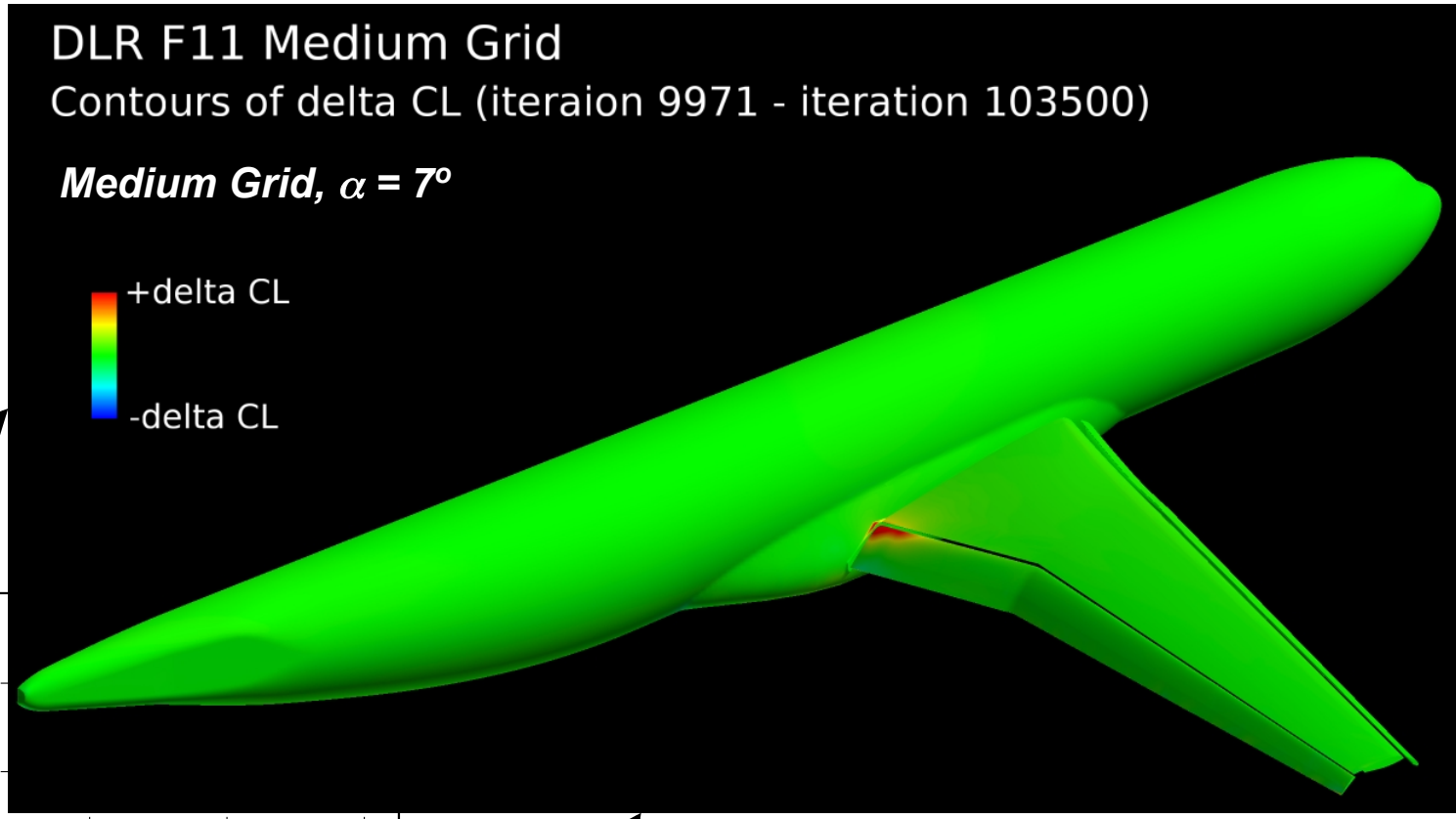
Fine

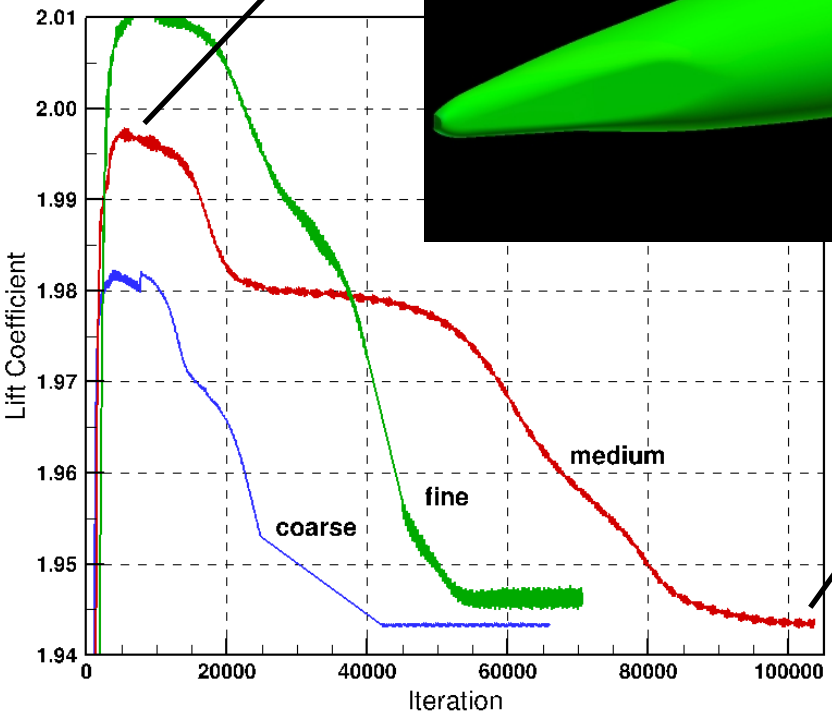


Standard deviation on C_L ranged from 0.0001 to 0.001

Convergence History

Case 1 C_L – Low Alpha Side-of-Body Flow Field





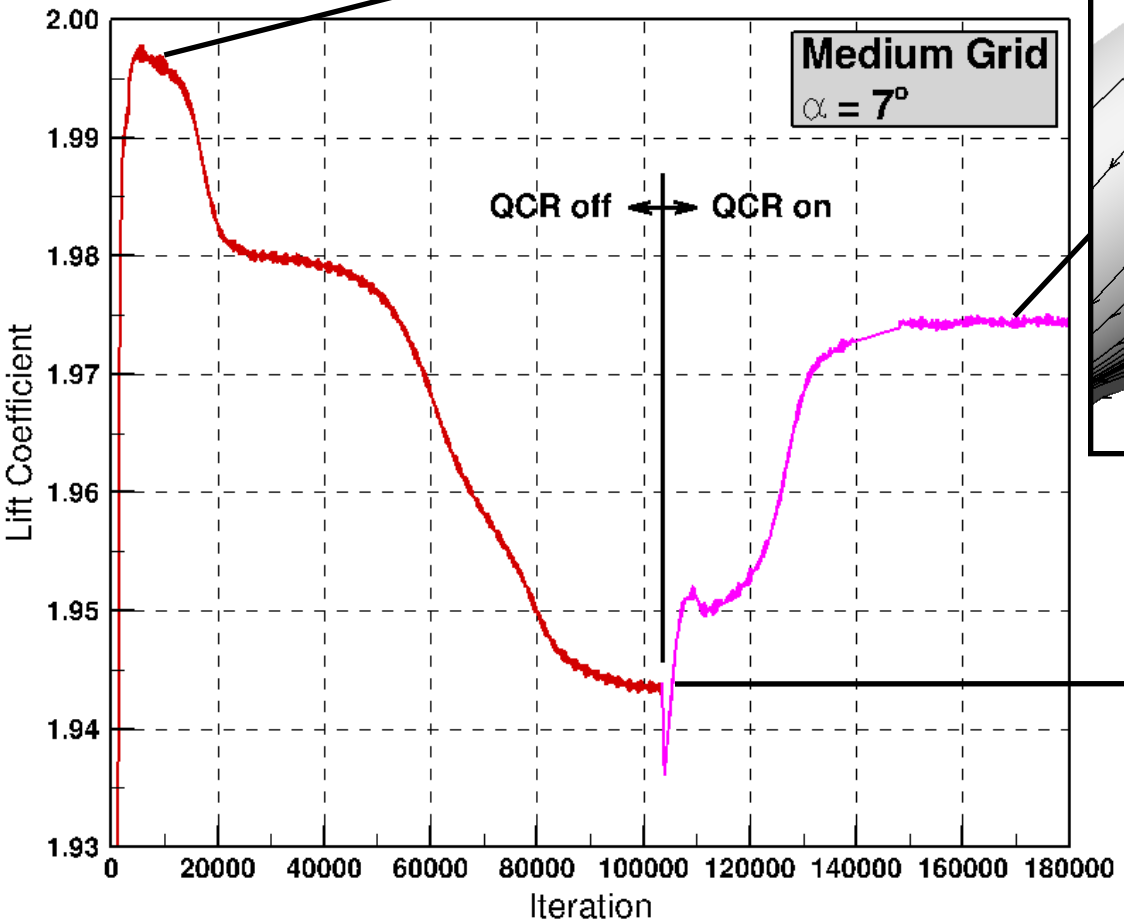
Lift change isolated to side-of-body

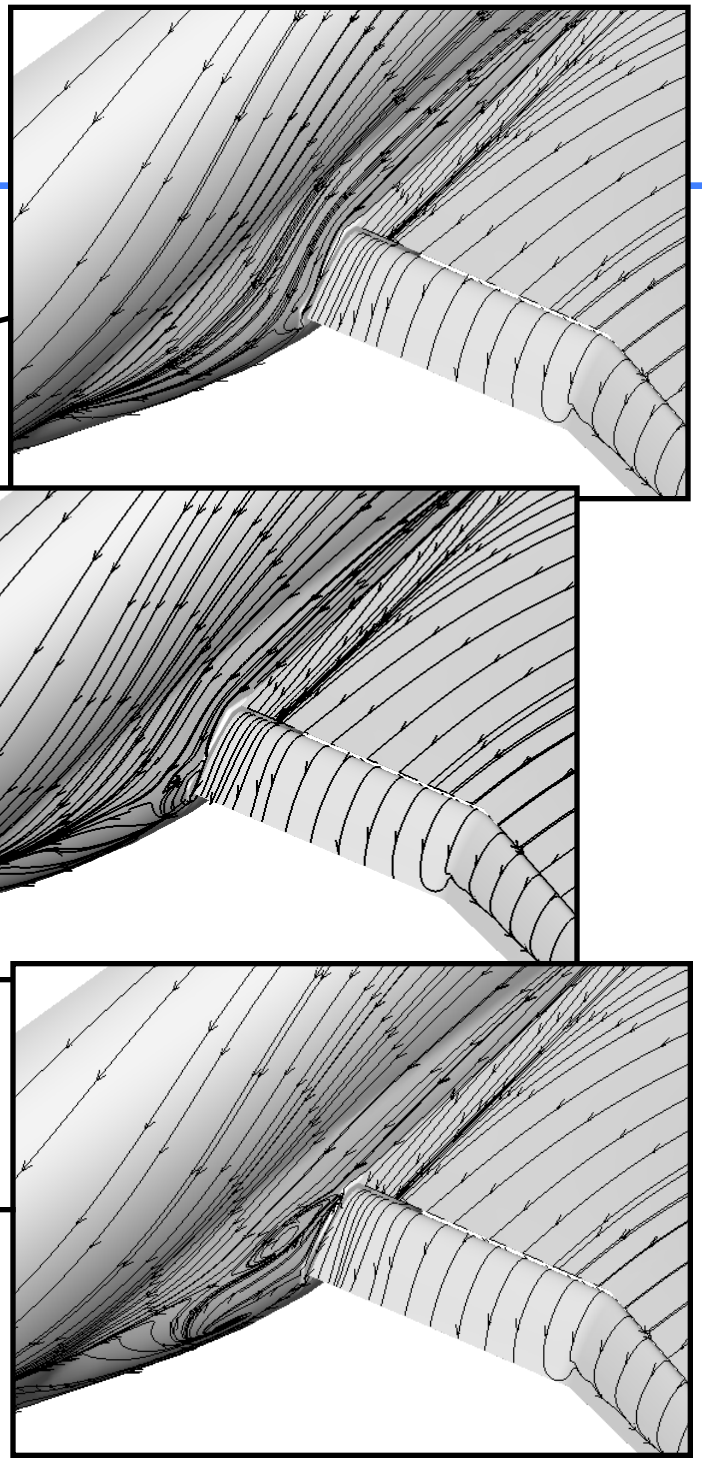
Convergence History
Case 1 C_L – QCR Effect

F11 Config 2: Slat Brackets / Flap Fairings Off

Mach = 0.175, Reynolds number = 15.1 million

Fully Turbulent, Free Air

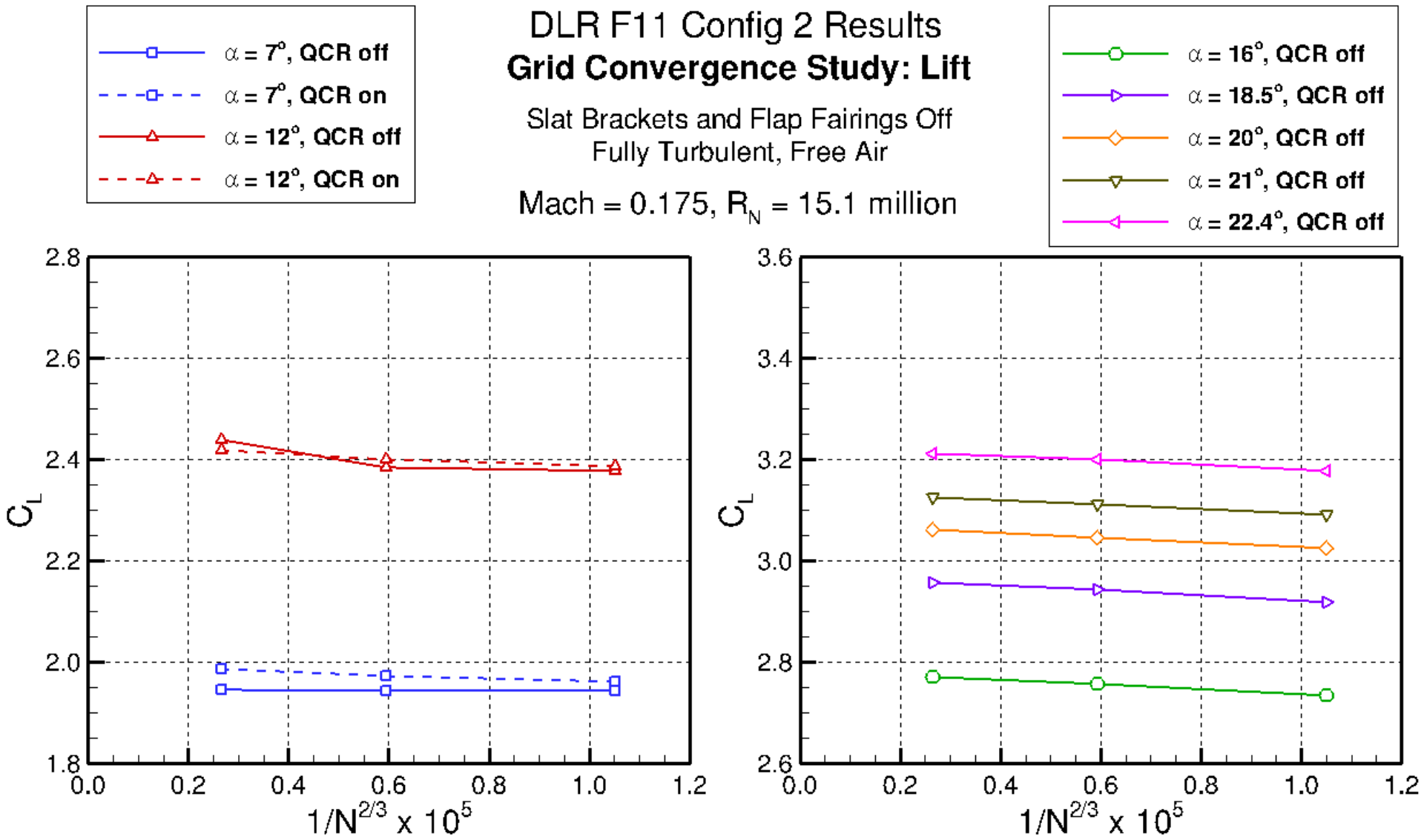




Test Case 1

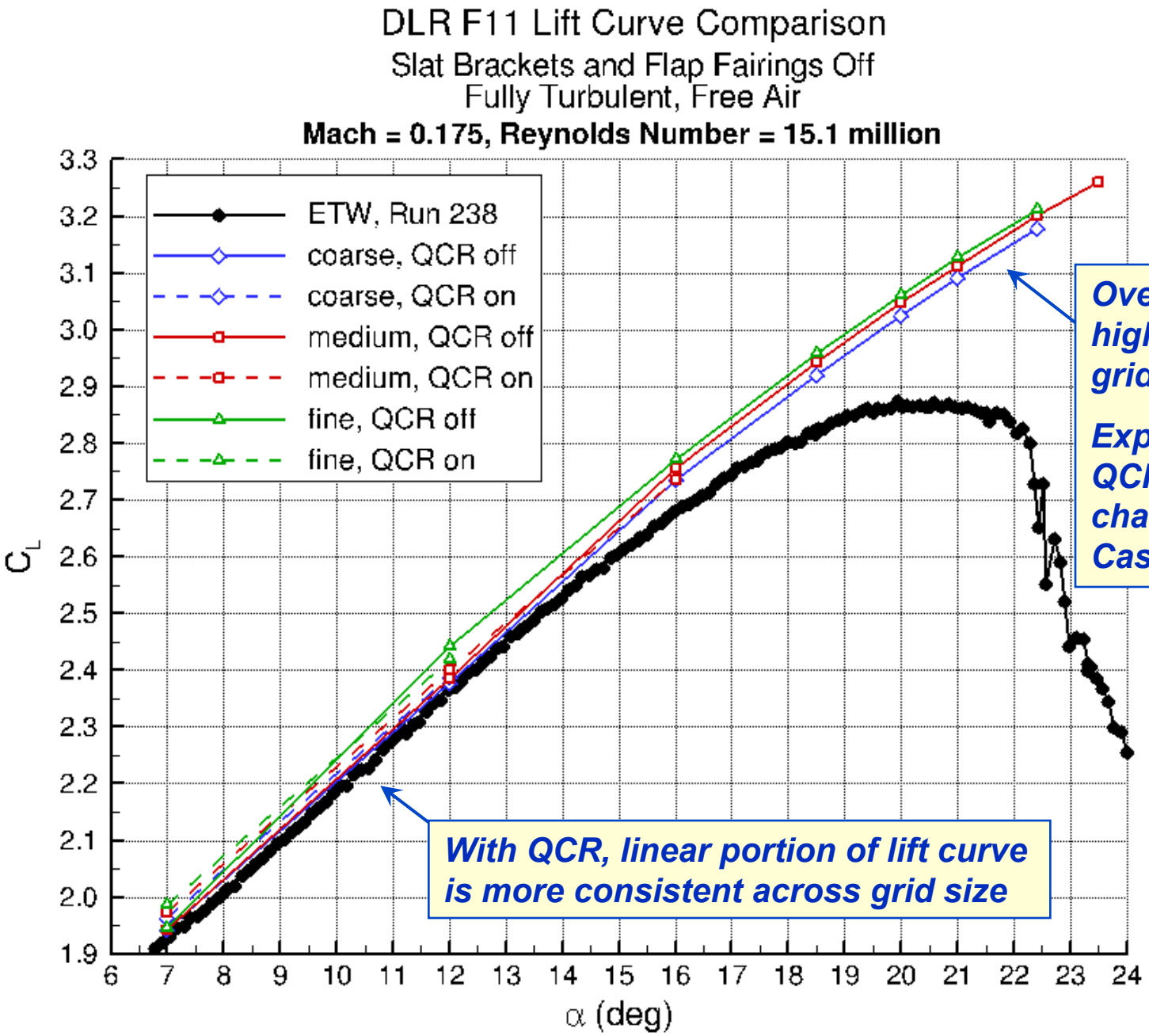
Grid Convergence Study

Test Case 1 – Grid Convergence Study
Lift Trend with Grid Density



Using QCR for the lower angles, all lift trend lines are linear and relatively flat with grid refinement → method appears to be 2nd order accurate

Test Case 1 – Grid Convergence Study
Lift Curve Comparison



Over-predicting C_L at higher alphas for all grid densities analyzed

Explored the effect of QCR on stall characteristics for Test Case 2a/b

With QCR, linear portion of lift curve is more consistent across grid size

Test Case 1 – Grid Convergence Study

Brackets / Fairings Off, QCR Off, α = 16°

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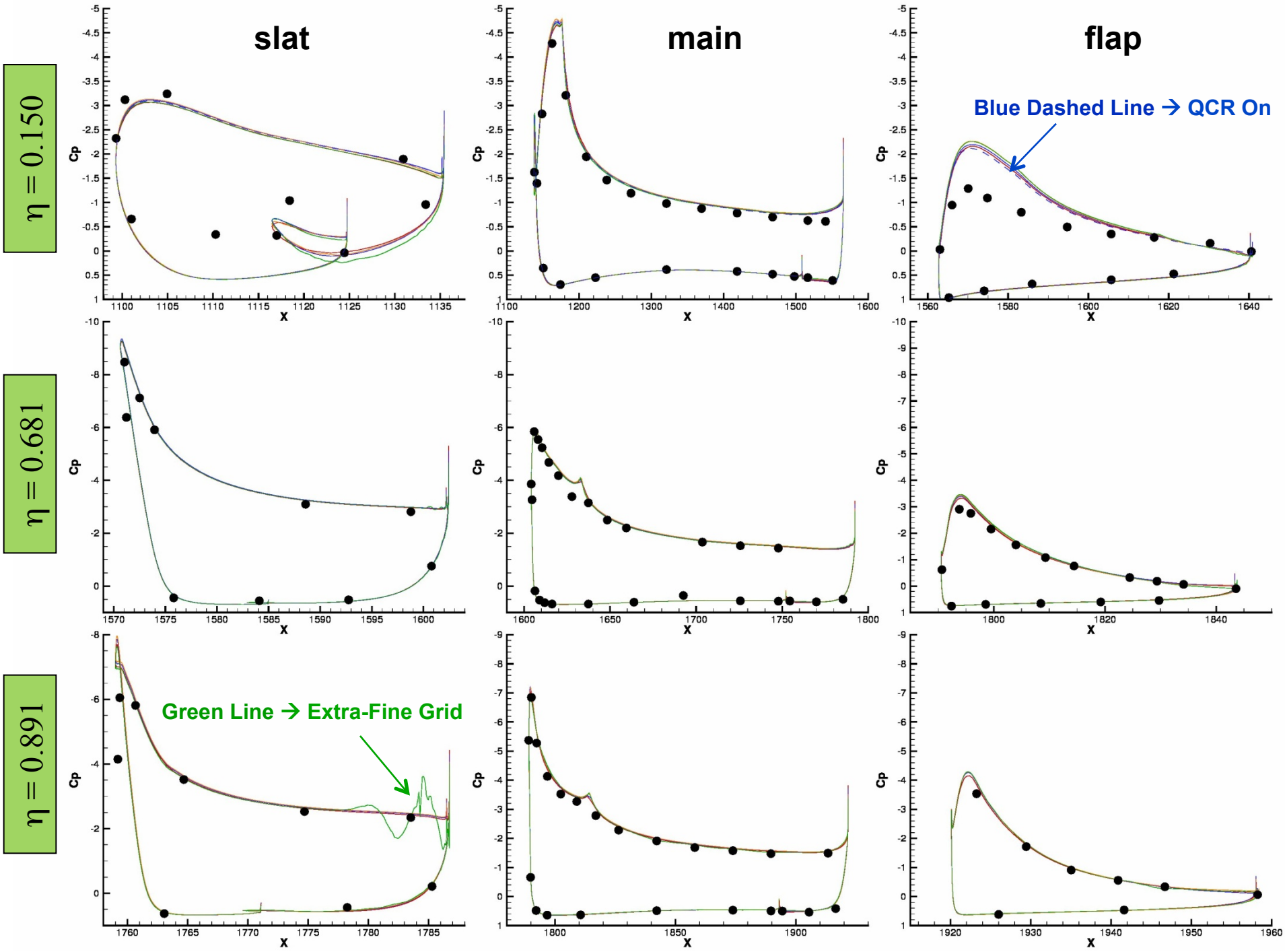
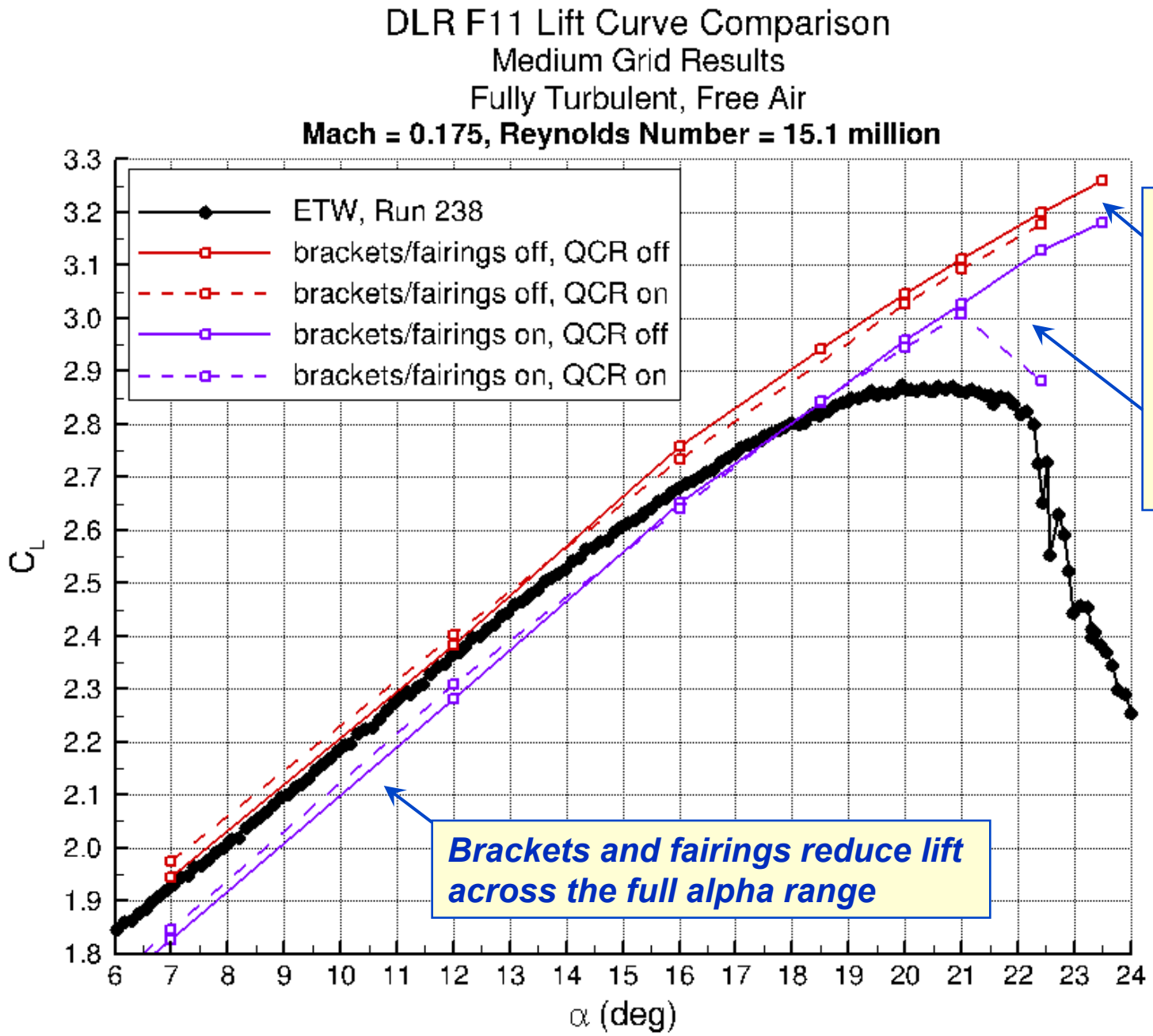


Test Case 2

Reynolds Number Study

Test Case 2 – Reynolds Number Study

Lift Curve Comparison: Effect of Brackets / Fairings



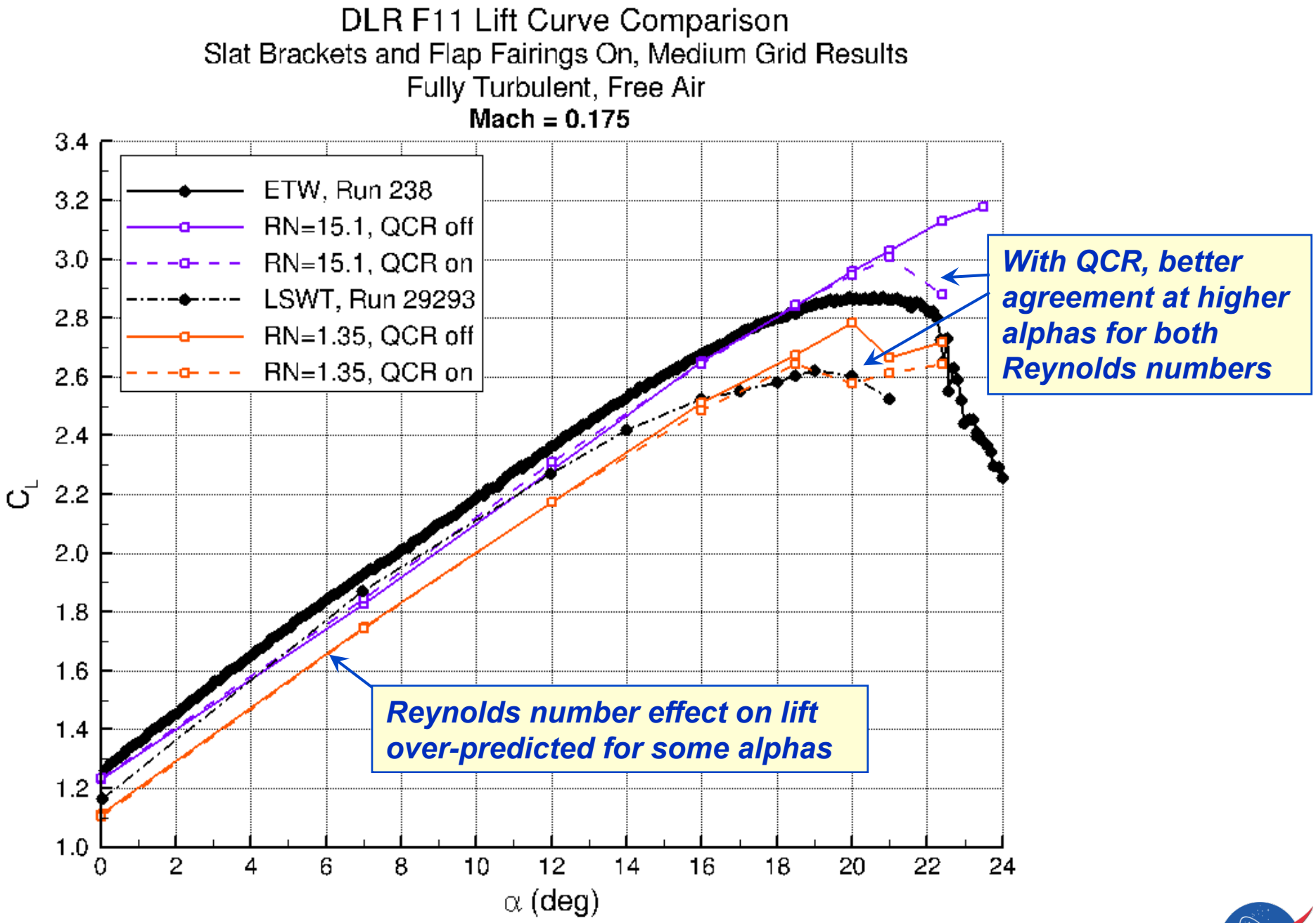
QCR Off: brackets / fairings do not alter stall behavior

QCR On: brackets / fairings force stall at 22.4°

Brackets and fairings reduce lift across the full alpha range

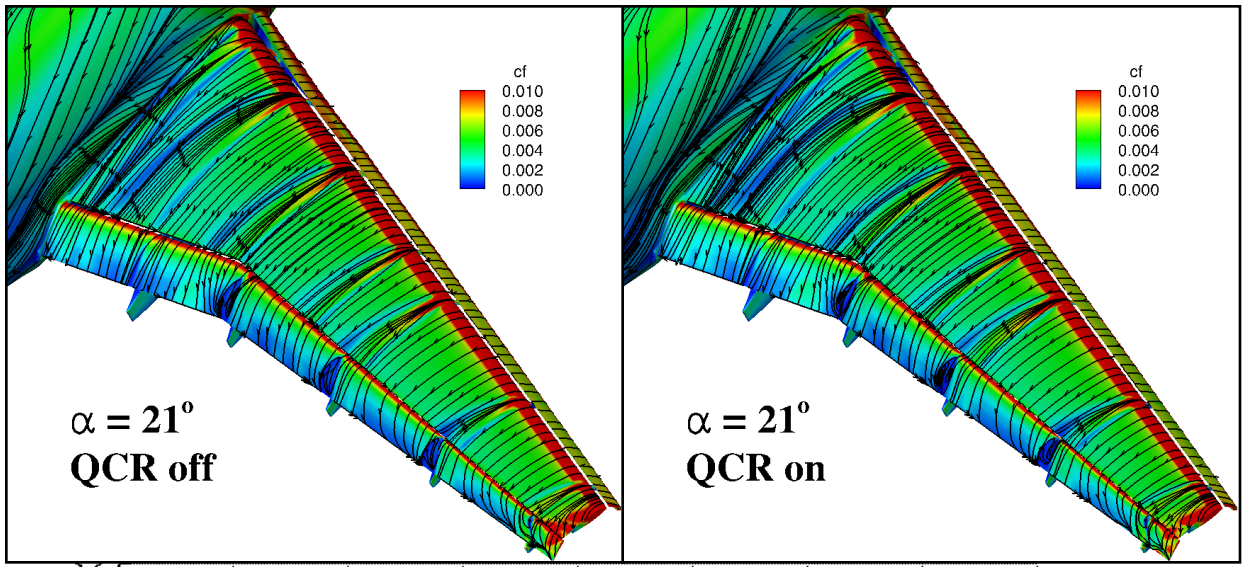
Test Case 2 – Reynolds Number Study

Lift Curve Comparison: Effect of Reynolds Number



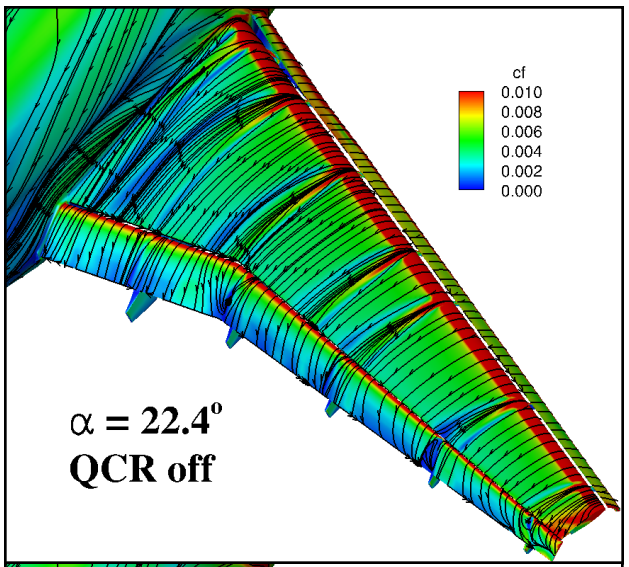
Test Case 2 – Reynolds Number Study

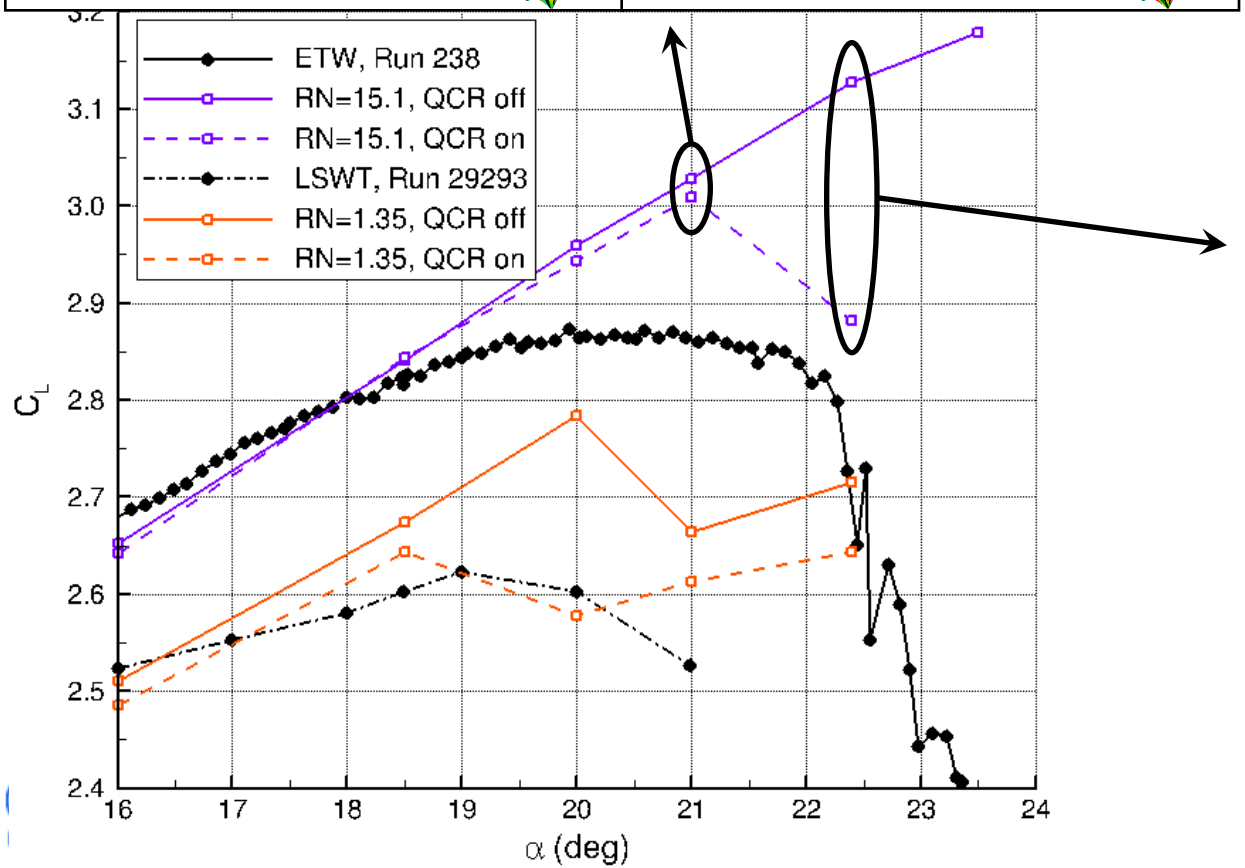
Effect of QCR at High AOA: RN = 15.1 million



Medium Grid Results

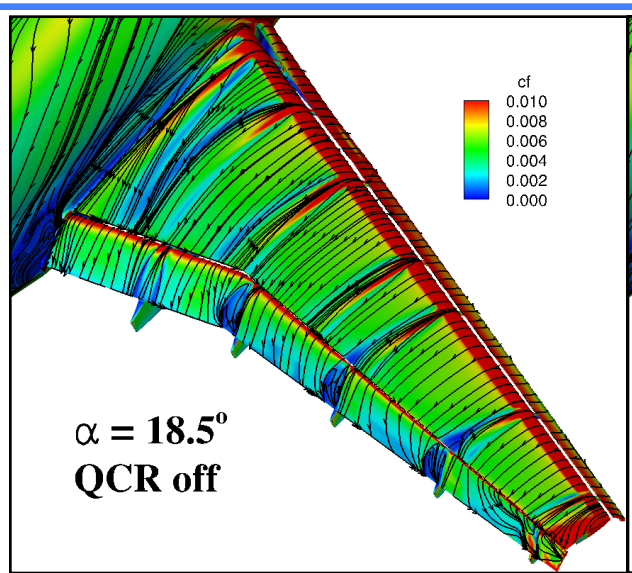
Mach = 0.175

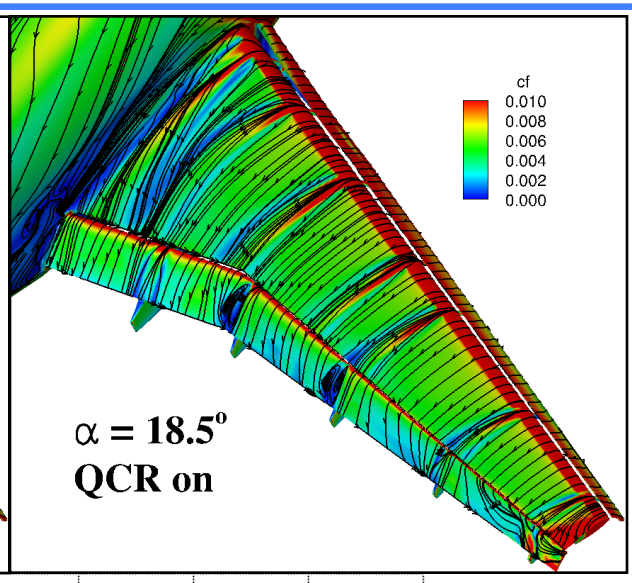




Test Case 2 – Reynolds Number Study

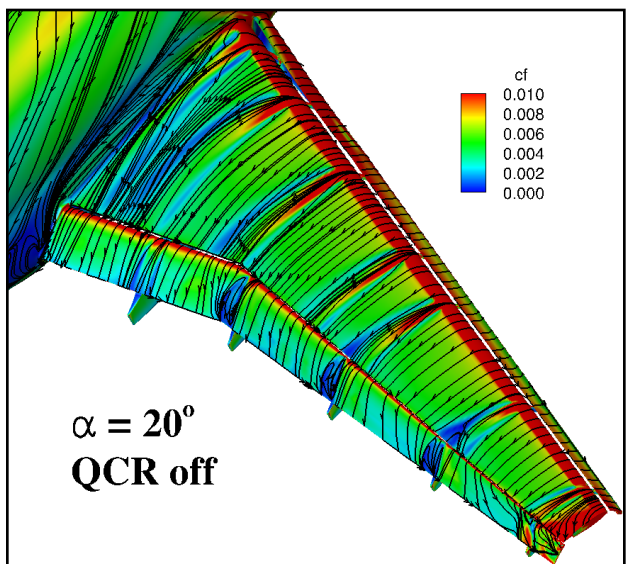
Effect of QCR at High AOA: RN = 1.35 million

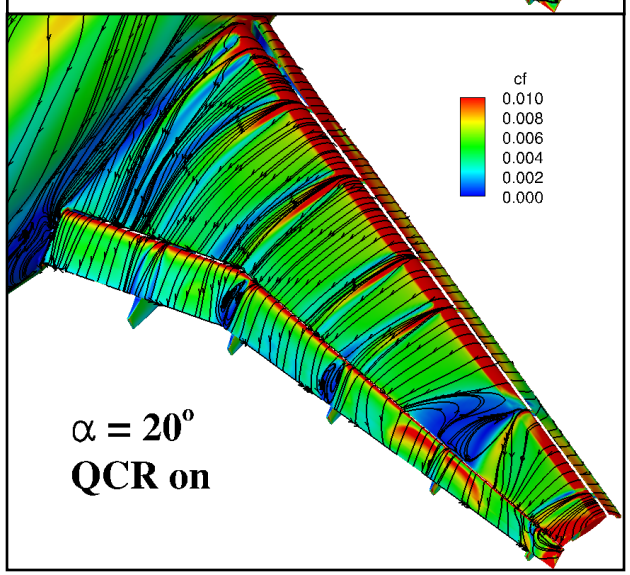


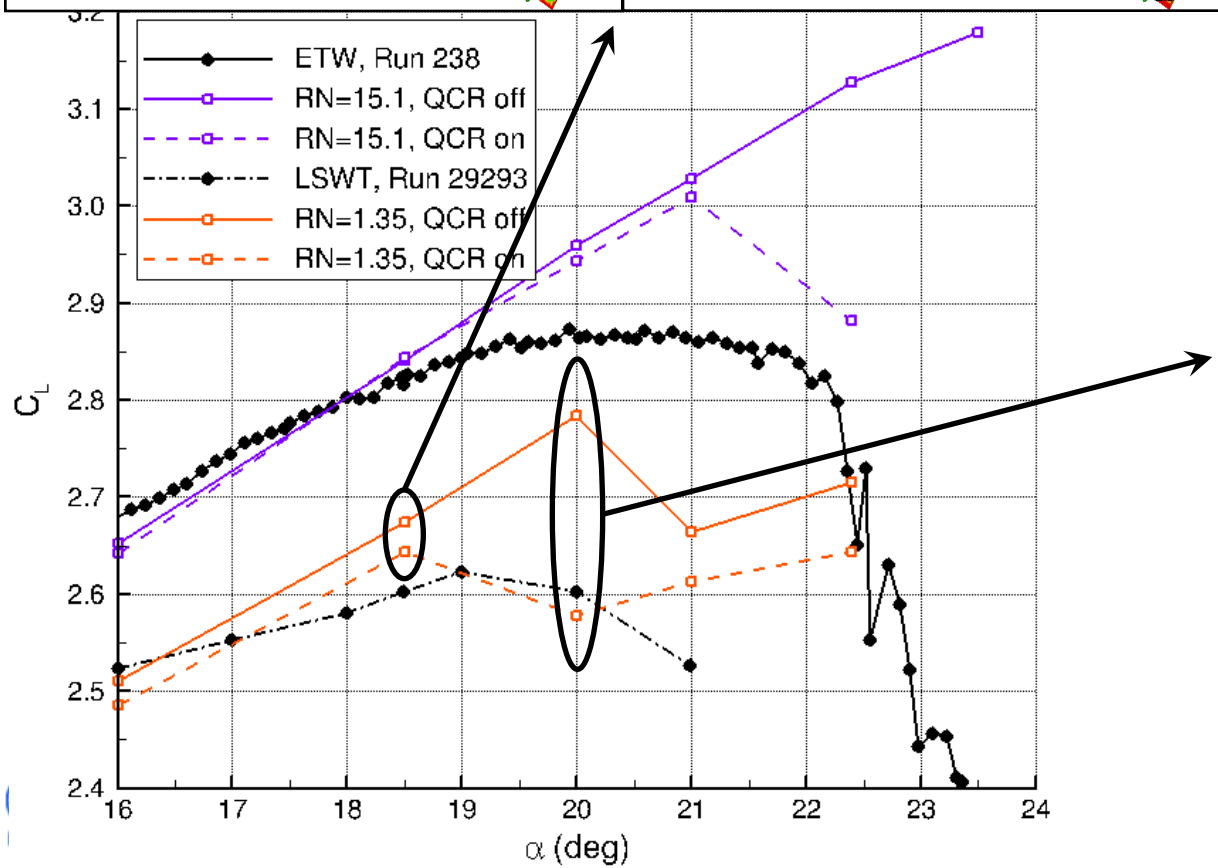


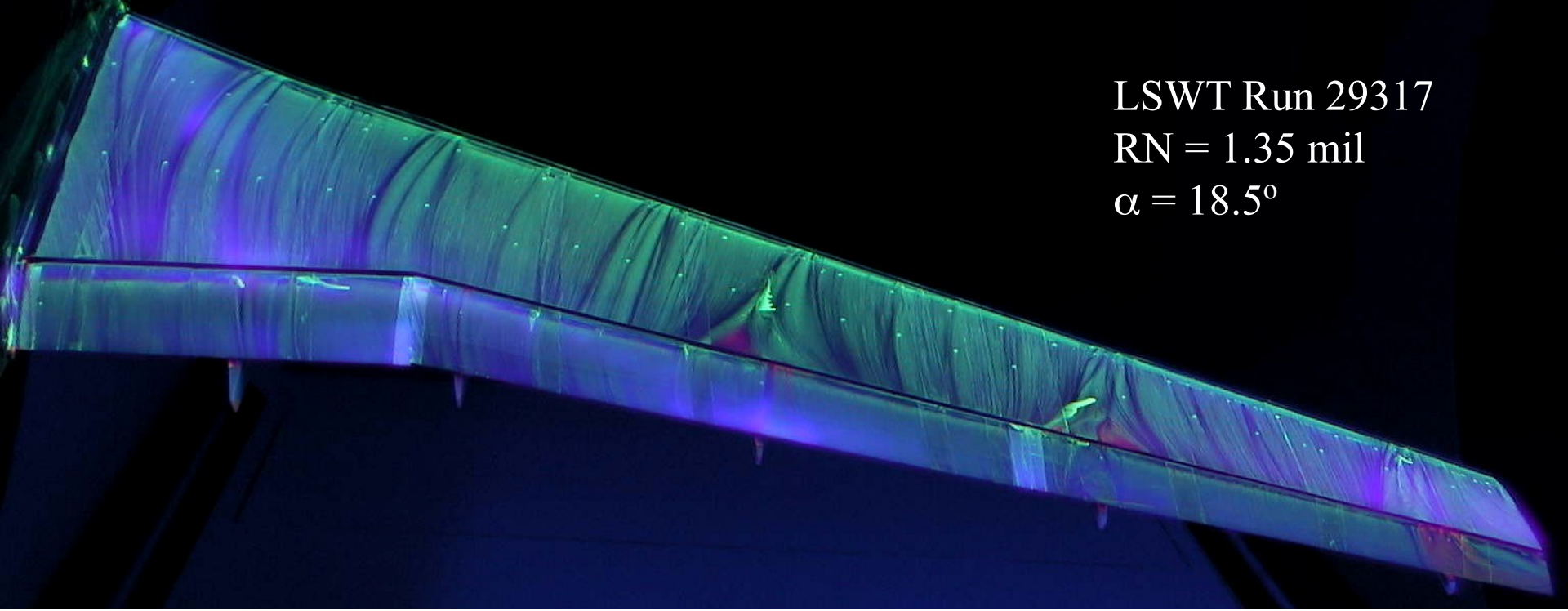
Medium Grid Results

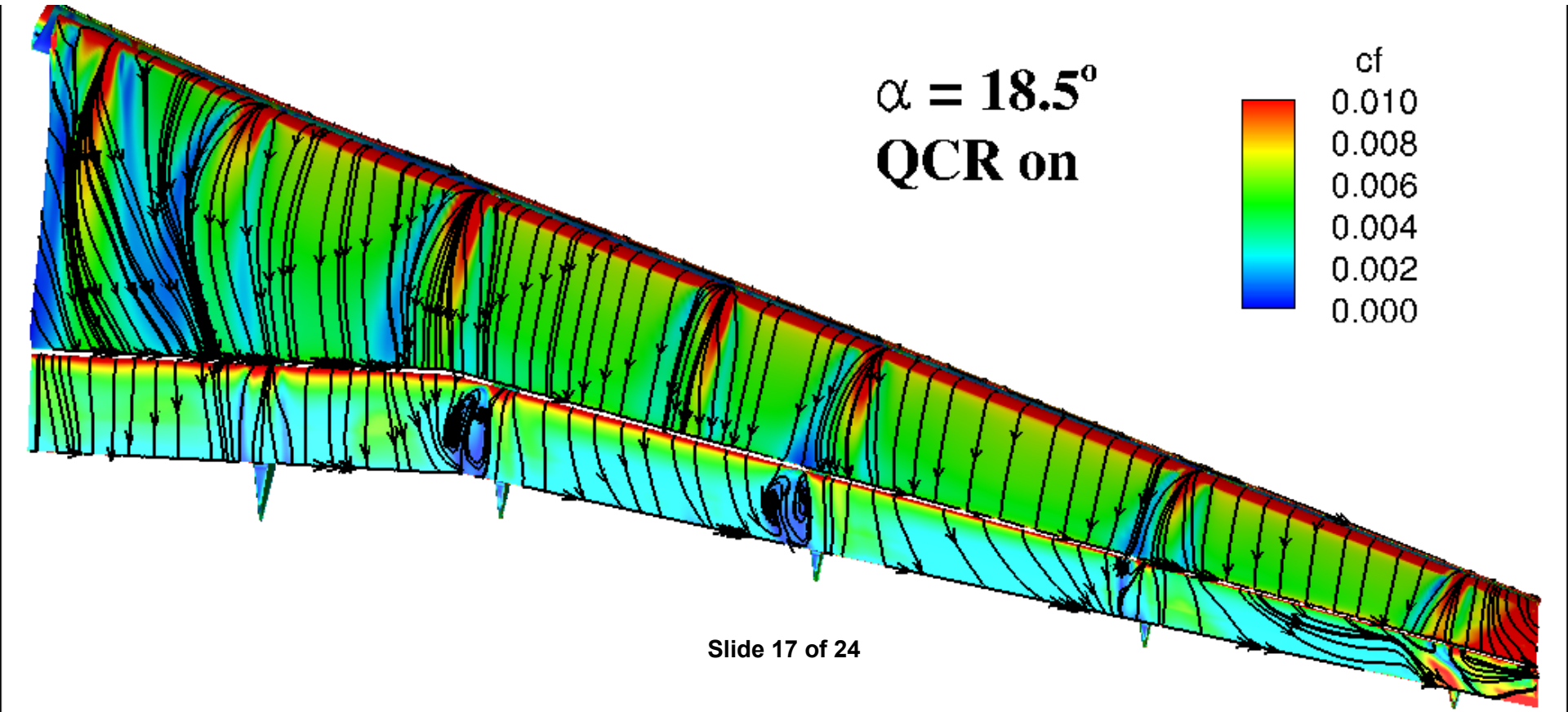
Mach = 0.175

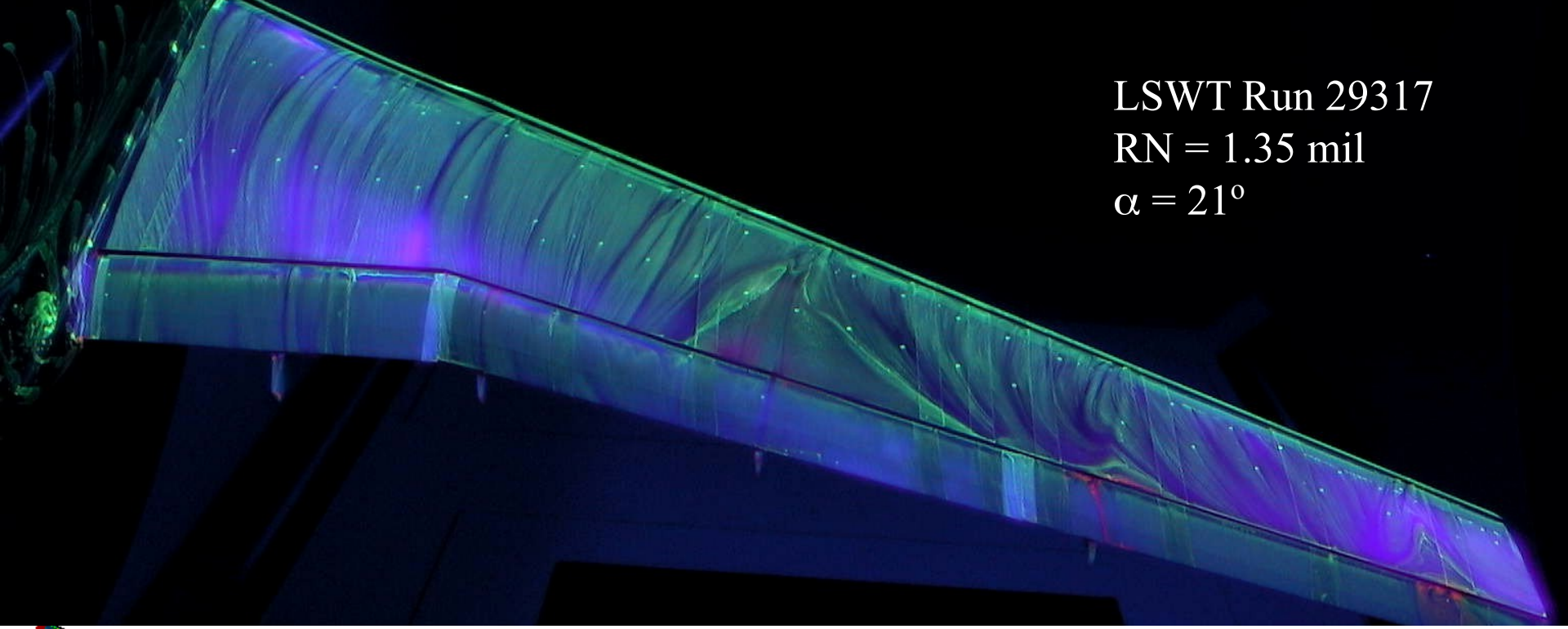


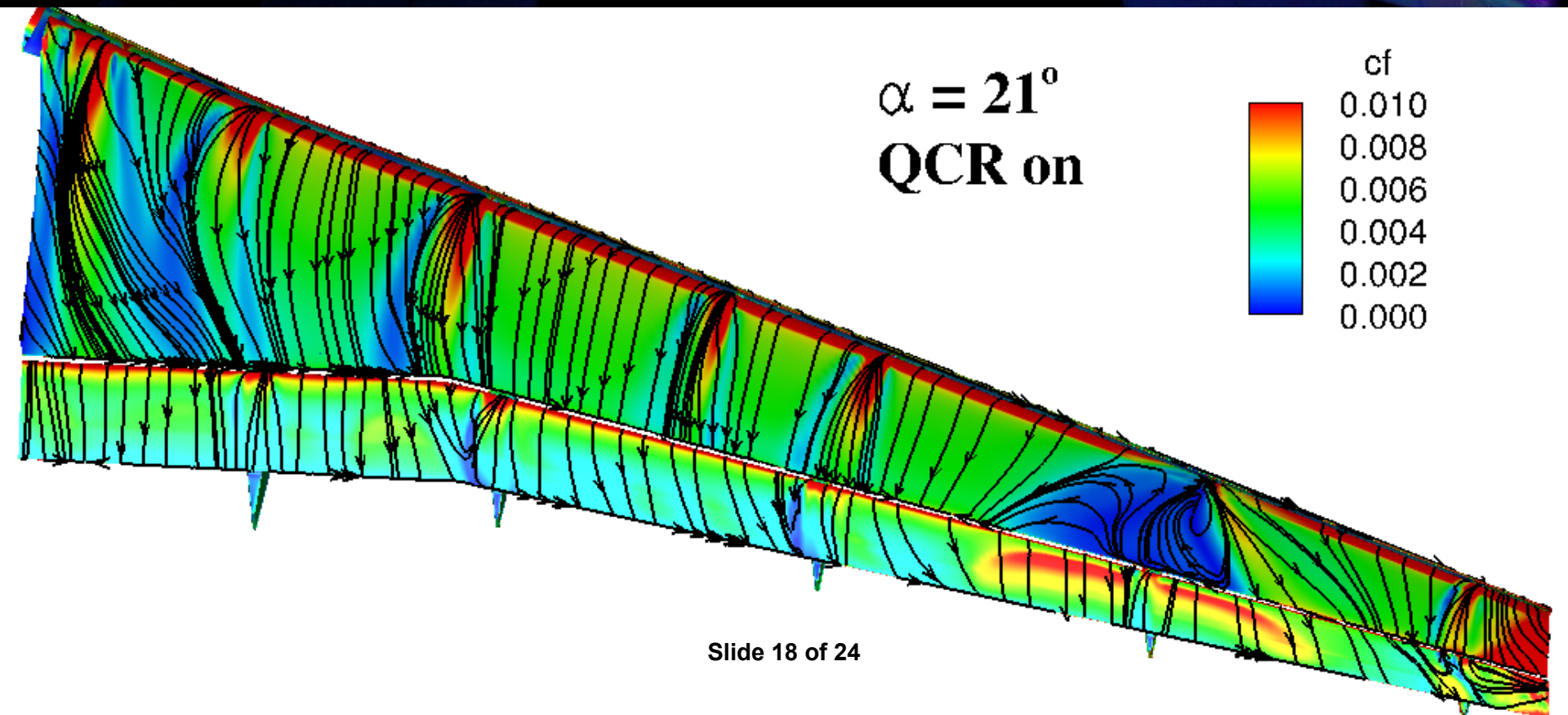





LSWT Run 29317
RN = 1.35 mil
α = 18.5°


α = 18.5°
QCR on
cf
0.010
0.008
0.006
0.004
0.002
0.000

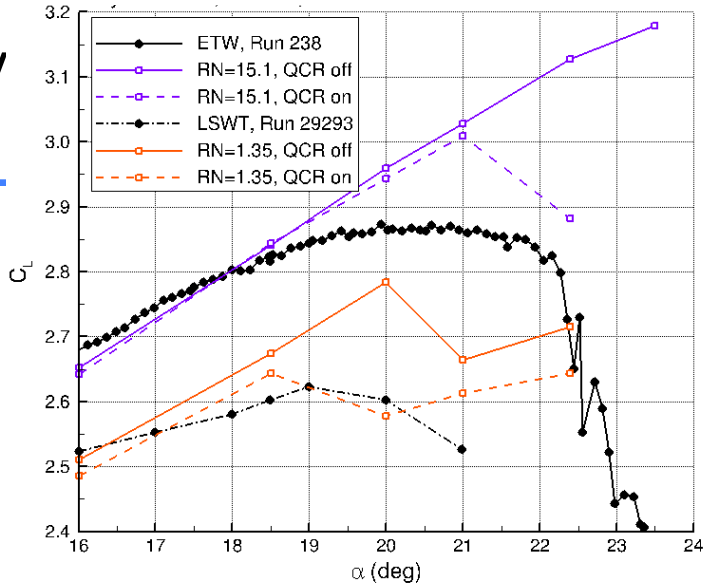

LSWT Run 29317
RN = 1.35 mil
α = 21°


α = 21°
QCR on
cf
0.010
0.008
0.006
0.004
0.002
0.000

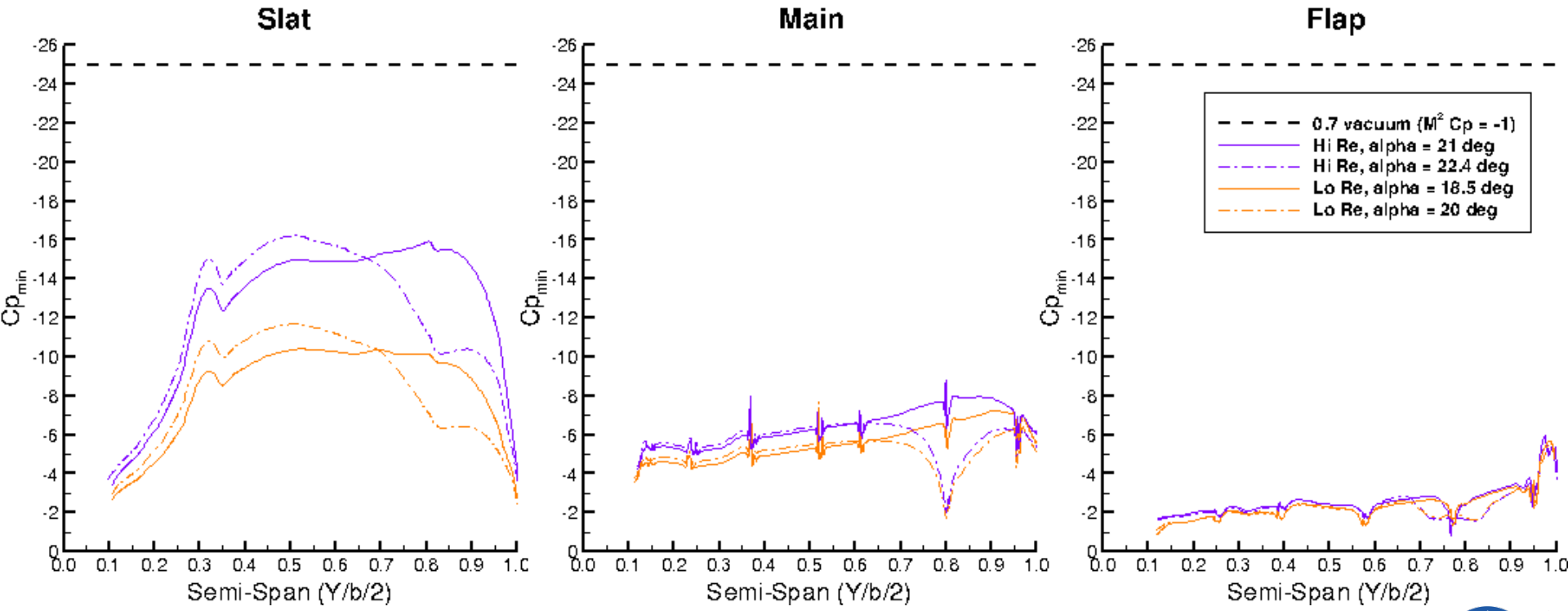
Test Case 2 – Reynolds Number Study
Minimum Cp Comparison

Based on J. P. Mayer's 0.7 vacuum correlation where $M^2_\infty C_p = -1$ was found to be an upper bound from NACA test data:

- ***Computed stall boundary does not appear to be driven by high suction peaks***
- ***This fact together with the subtle round-over character of the lift curve suggest main element stall is driven by TE separation***



Mach = 0.175 / Slat Brackets and Flap Fairings On / Medium Grid / QCR on



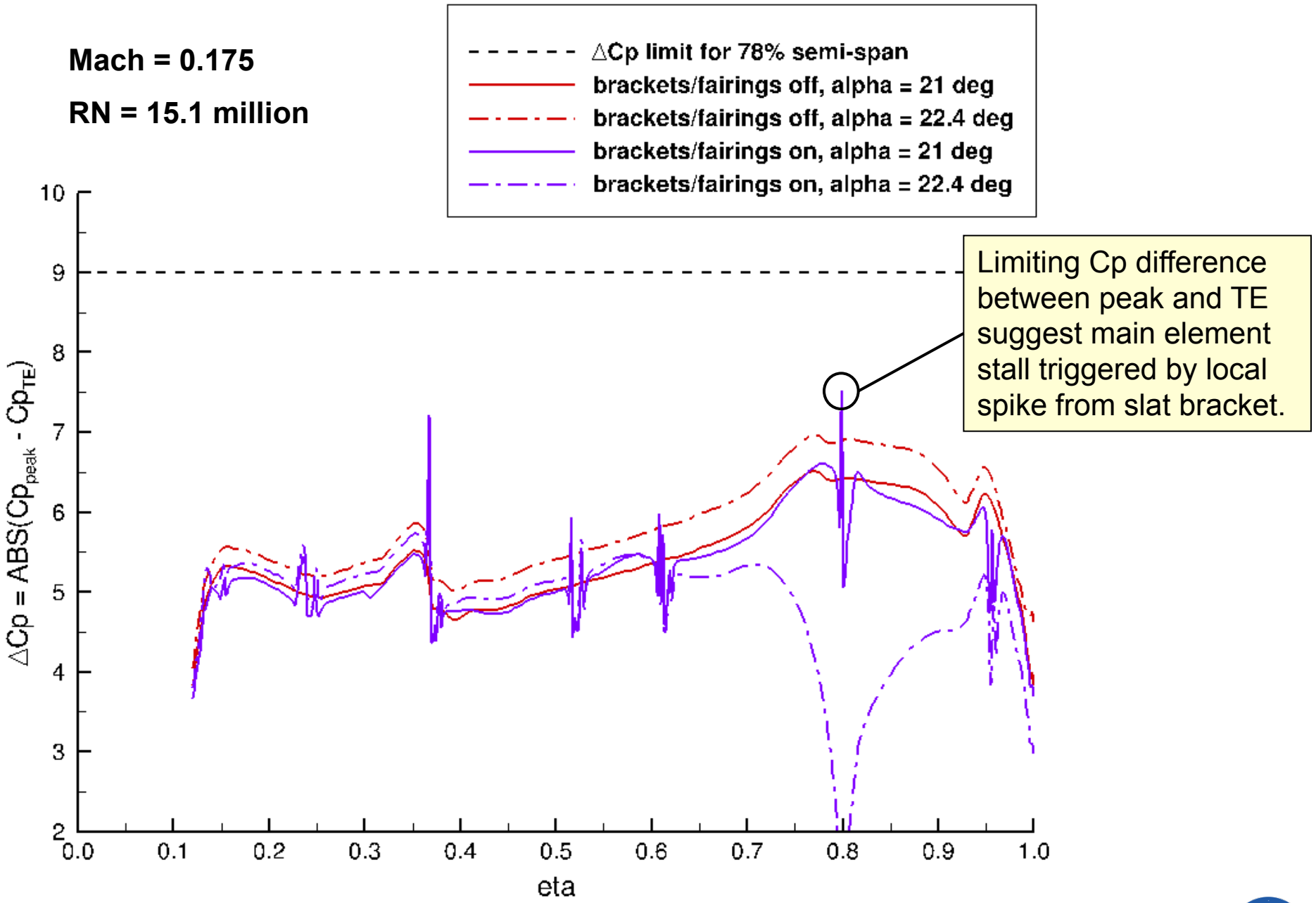
Test Case 2 – Reynolds Number Study

Pressure Difference Rule for Main Element

Pressure Difference Rule
Valarezo, W. O., Chin, V. D., "Method for the Prediction of Wing Maximum Lift," Journal of Aircraft Vol. 31, No. 1, Jan-Feb 1994

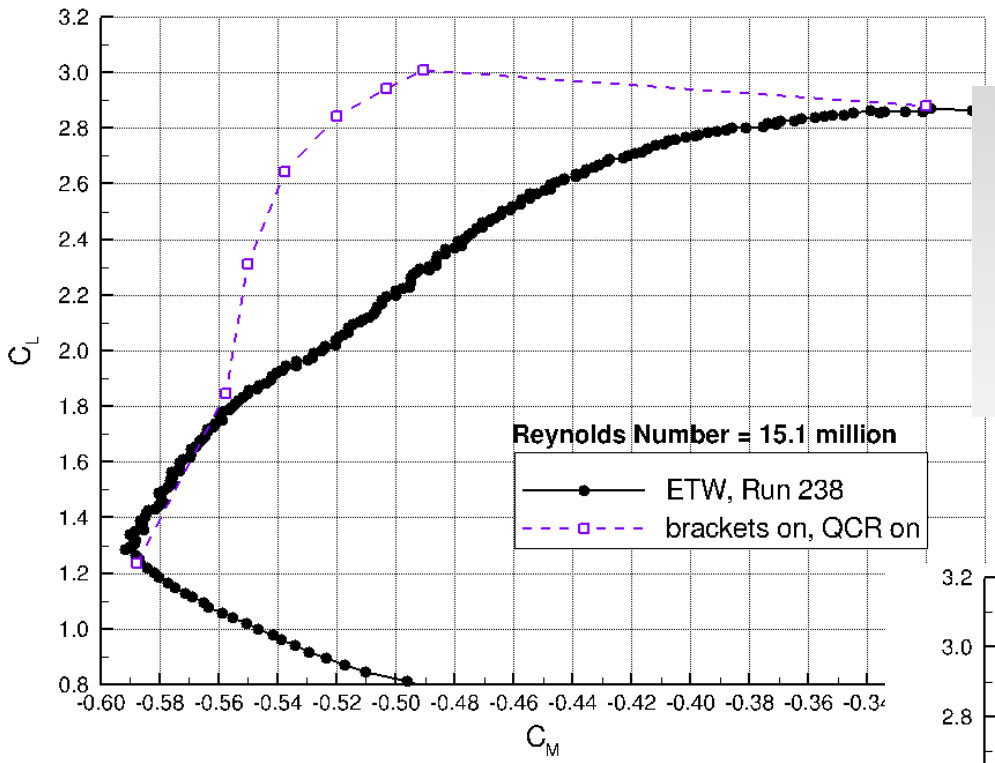
Mach = 0.175

RN = 15.1 million



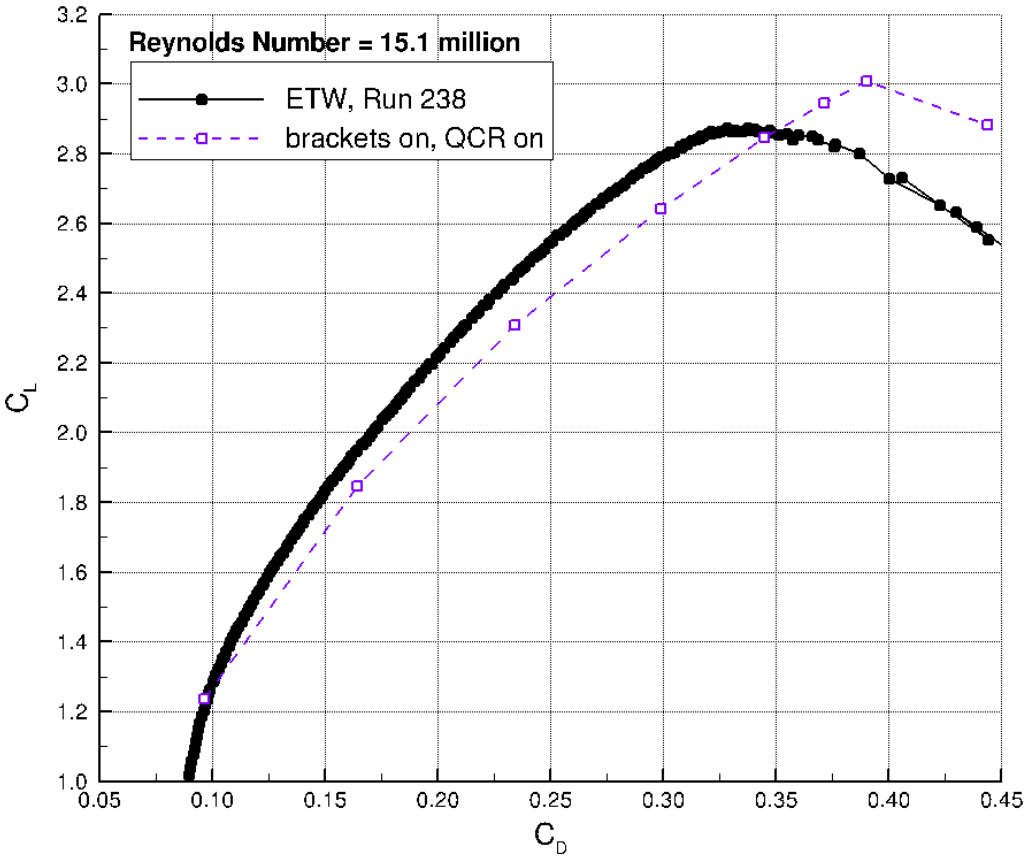
Test Case 2b – Reynolds Number Study

Pitching Moment and Drag Polar Comparisons



- ***Good agreement in CM at two lowest alphas of 0 and 7 degrees.***
- ***Pitching moment for alphas of 12 through 21 degrees significantly more nose-down compared to experiment.***

- ***Drag polar is rotated compared to ETW data with very good agreement at 0 degrees and ~300 counts more drag computed at alpha = 16 degrees.***



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DLR F11 OVERFLOW Analysis
Conclusions

- Uniform grid refinement does not have a big effect on pressures or stall
- QCR had a significant effect at both low and high angles of attack
  - alters off-body flow field at side-of-body for 7° and 12°
  - forces stall to occur at 22.4° for high RN and 20° for low RN
- Trailing edge stall occurs on the main element with full-chord separation at:
  - Experiment → ~50% semi-span or behind slat bracket #5
  - OVERFLOW → ~80% semi-span or behind slat bracket #6
- More study is needed to determine why we missed the critical wing station

F11 stall characteristics driven by interaction between bracket wakes and main element boundary layer

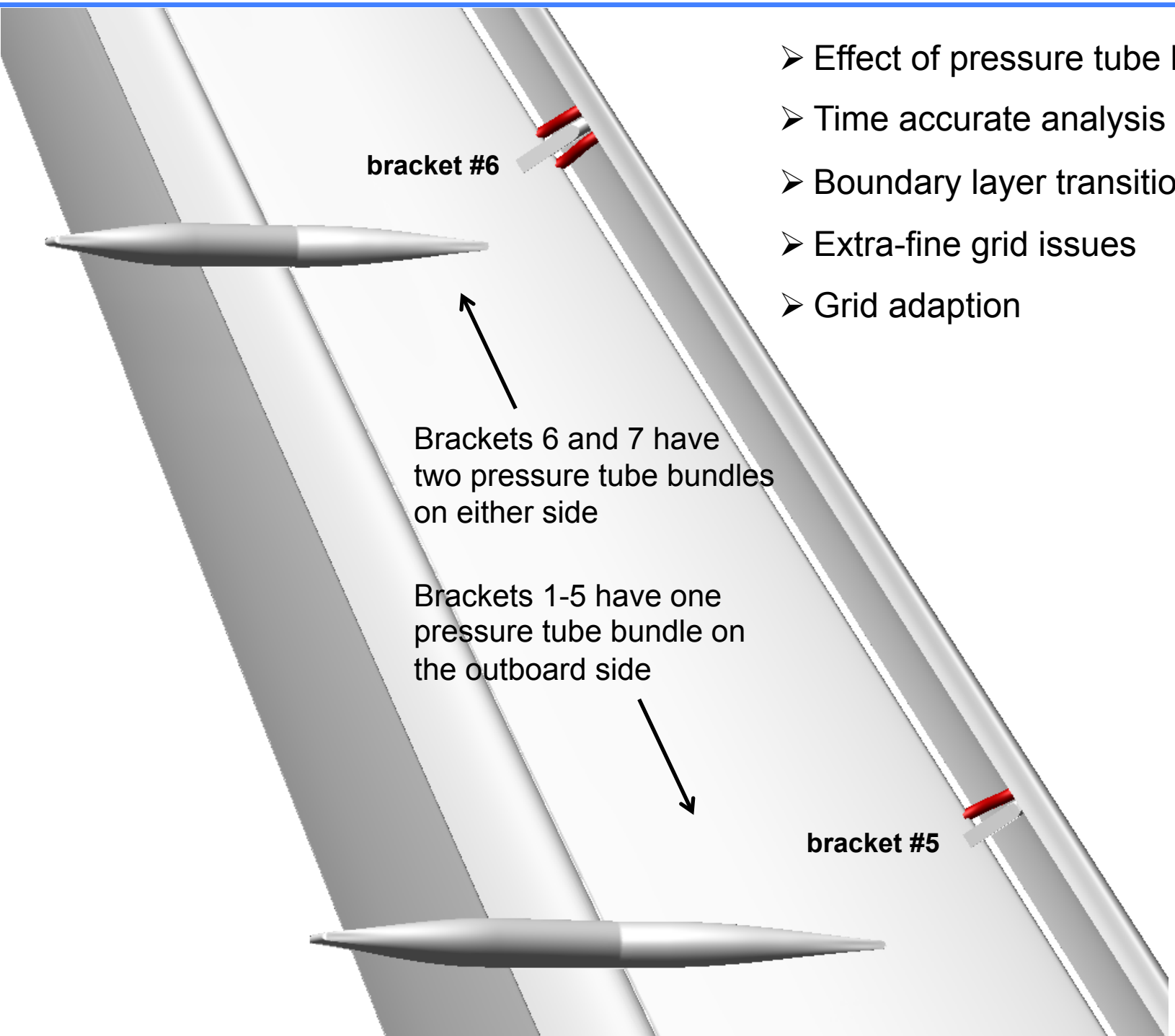
Trap Wing exhibits leading edge stall and we saw better agreement

Trailing edge stall appears to be more challenging to accurately predict

DLR F11 OVERFLOW Analysis

Future Work

- Effect of pressure tube bundles
- Time accurate analysis
- Boundary layer transition
- Extra-fine grid issues
- Grid adaption



Acknowlegments

Grid Generation

- **Neal Harrison** and **Yoram Yadlin**, Boeing

Grid Consultation

- **John Vassberg**, Boeing
- **William Chan**, NASA Ames

Post-Processing

- **Feng Jiang**, Boeing

General Support/Consultation

- **Jeff Slotnick** and **John Vassberg**, Boeing

Thank You!

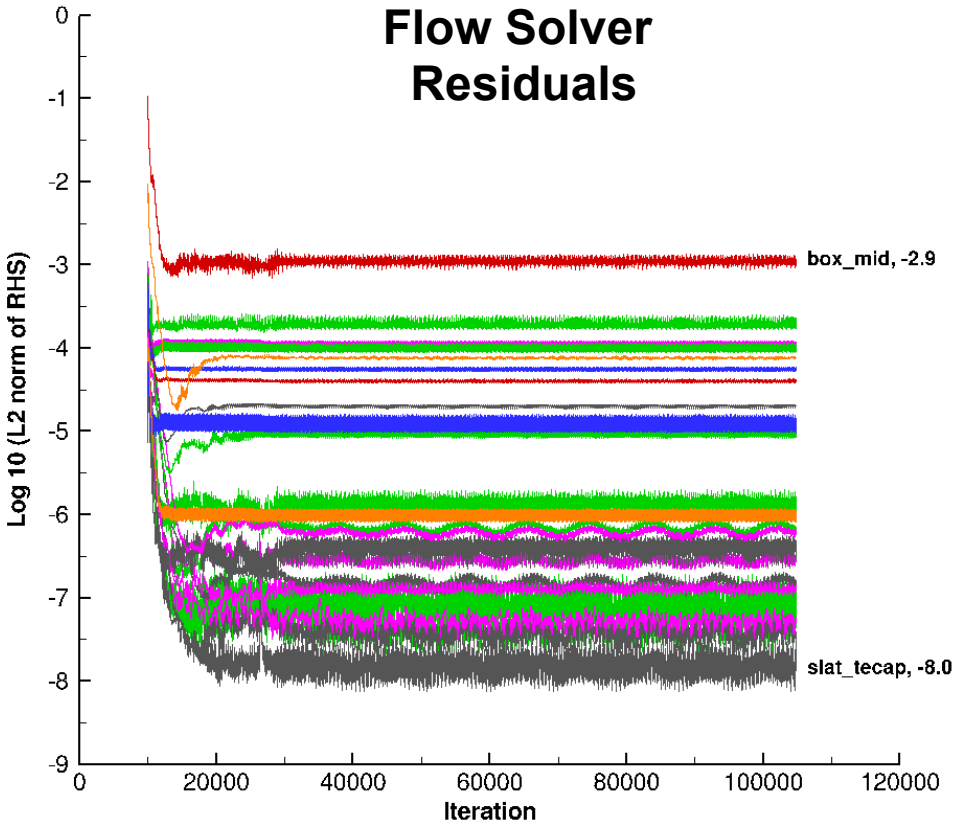
Steady State Convergence History
Case 1 Residuals

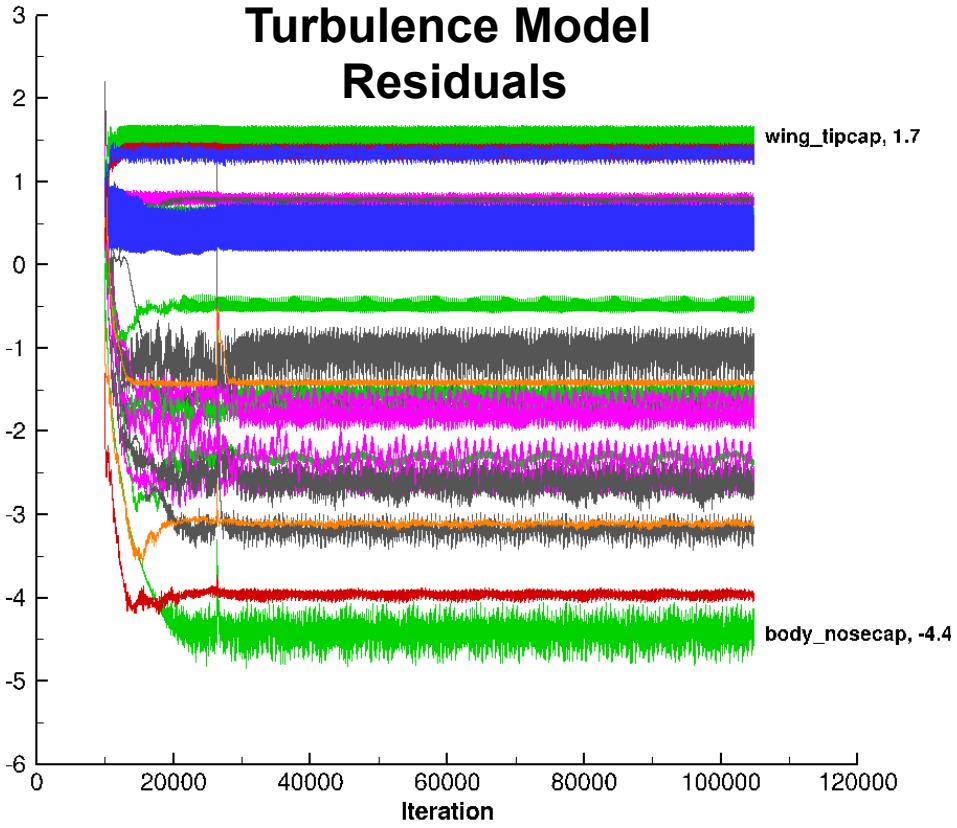
F11 Config 2: Slat Brackets / Flap Fairings Off

Mach = 0.175, Reynolds number = 15.1 million

Fully Turbulent, Free Air

Medium Grid, α = 16°

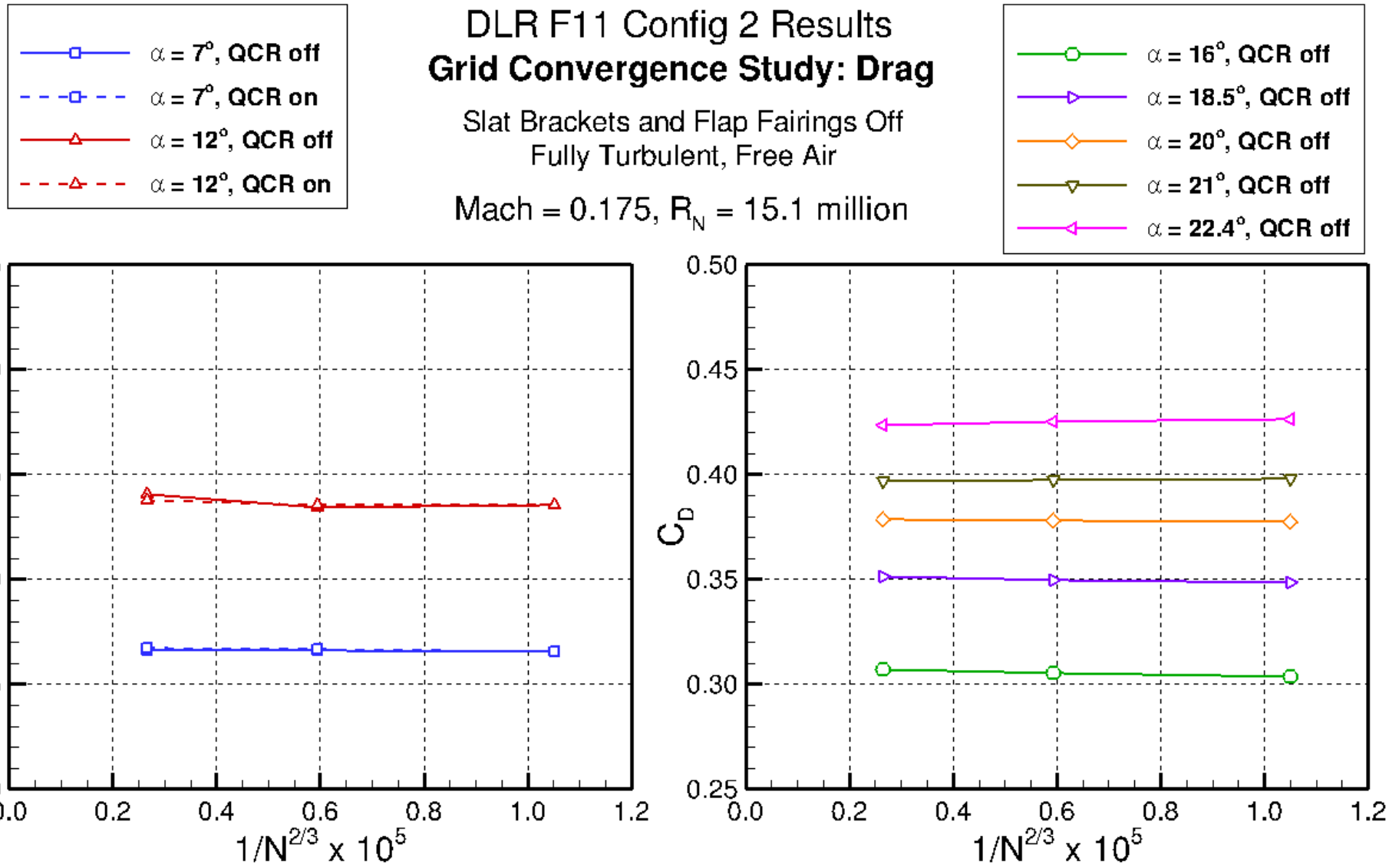




Test Case 1 – Grid Convergence Study

Drag Trend with Grid Density

CFD High Lift Prediction Workshop



With a relatively large drag scale (major tick = 500 counts), data form nearly straight lines as the grid is refined.

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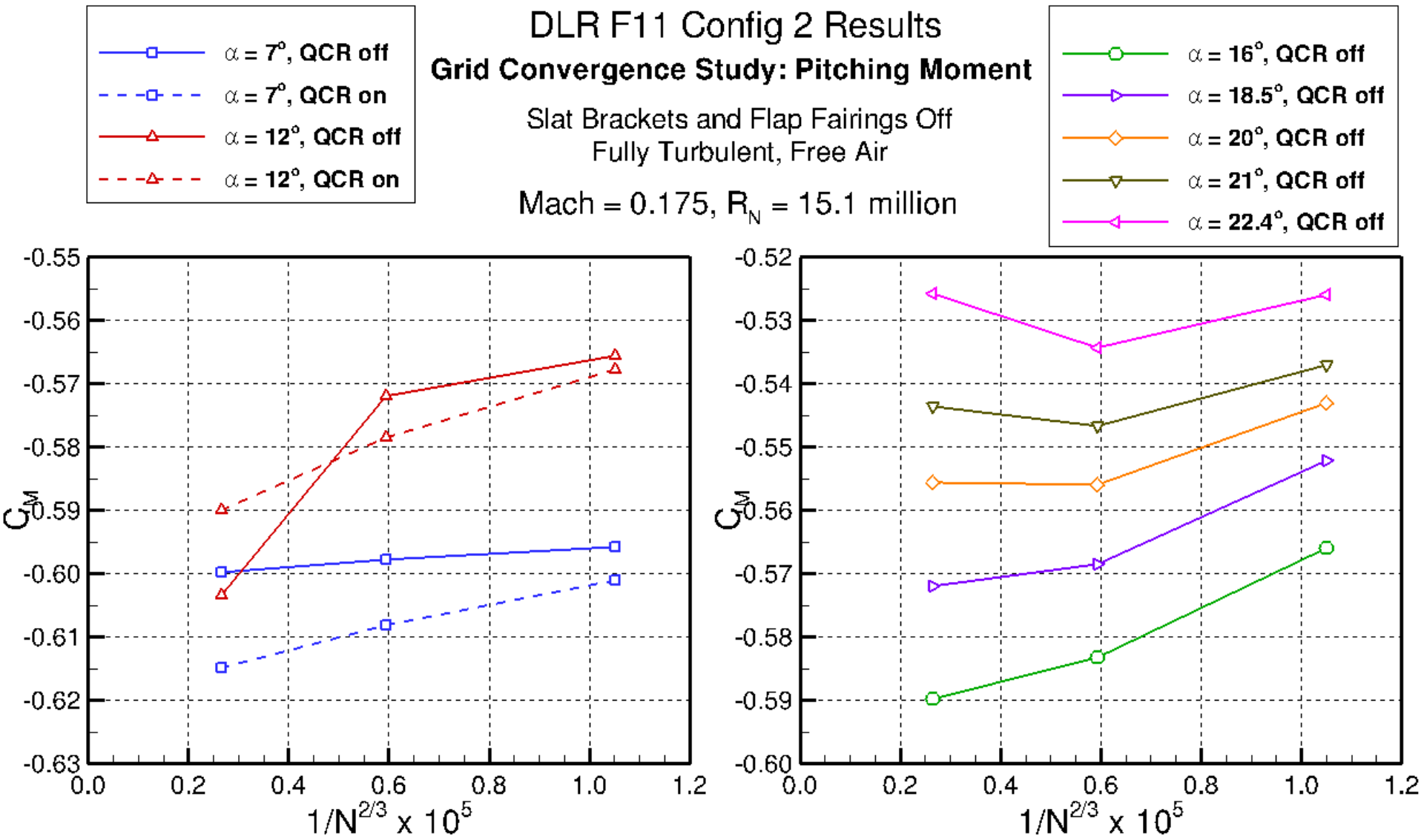
Test Case 1 – Grid Convergence Study
Pitching Moment Trend with Grid Density

CFD High Lift Prediction Workshop



Pitching moment trends are not linear with the highest alphas changing slope between medium and fine grid levels.

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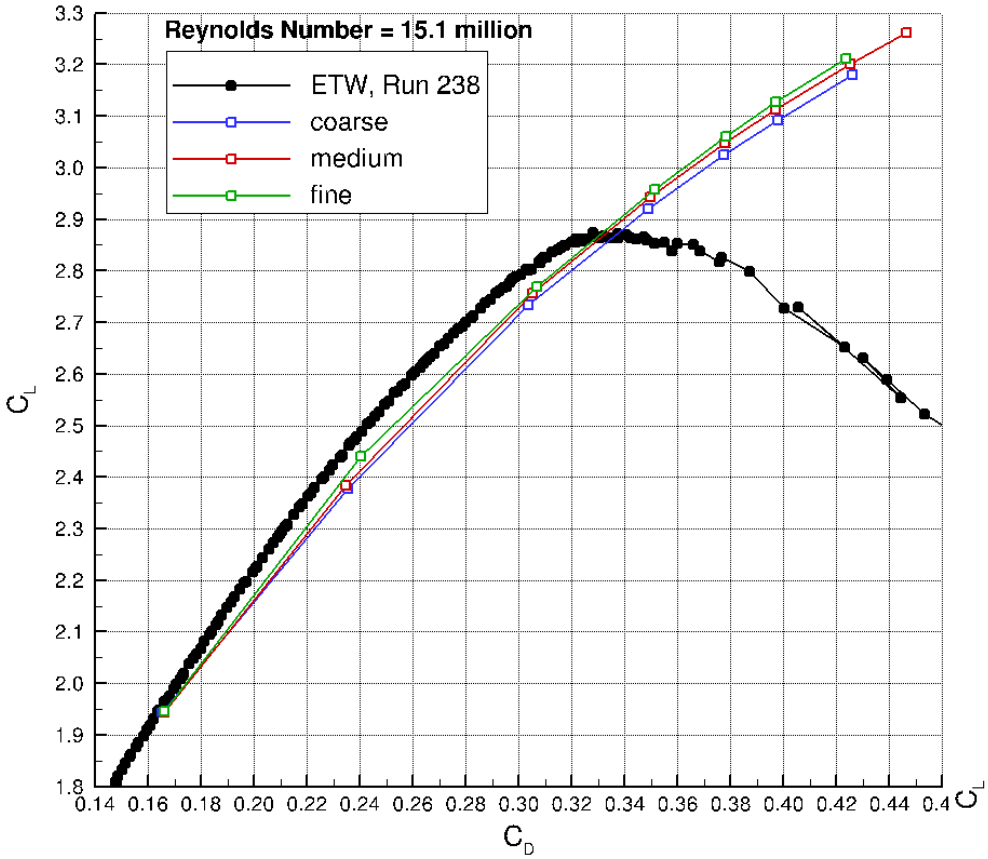
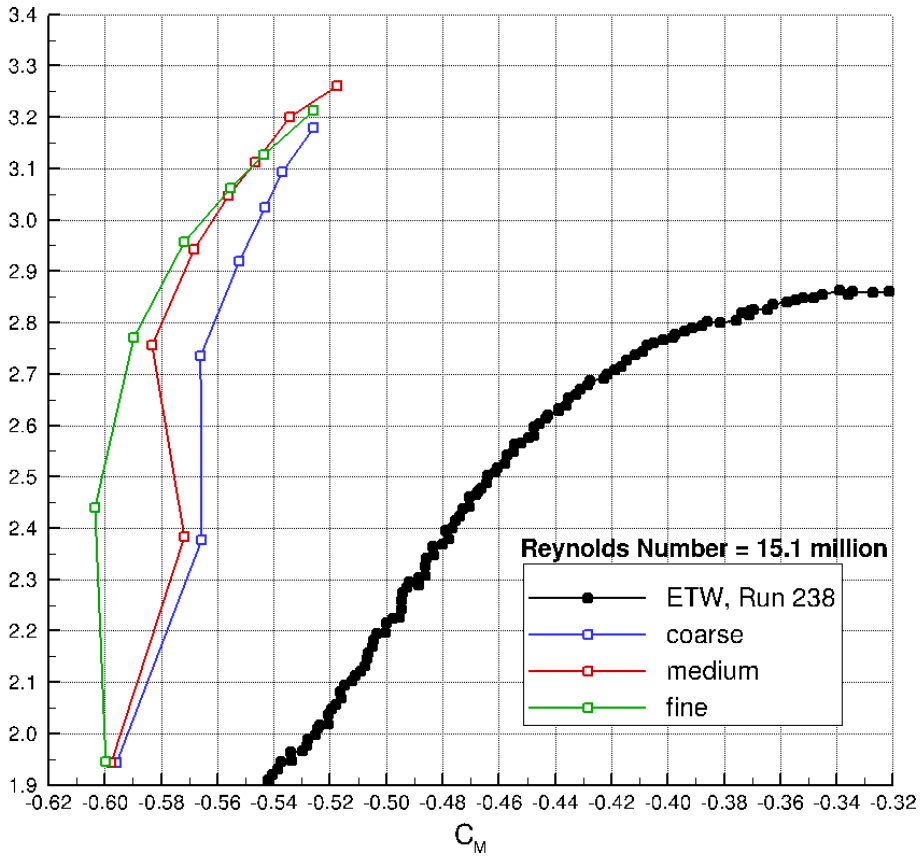
Test Case 1 – Grid Convergence Study

Pitching Moment and Drag Polar Comparisons

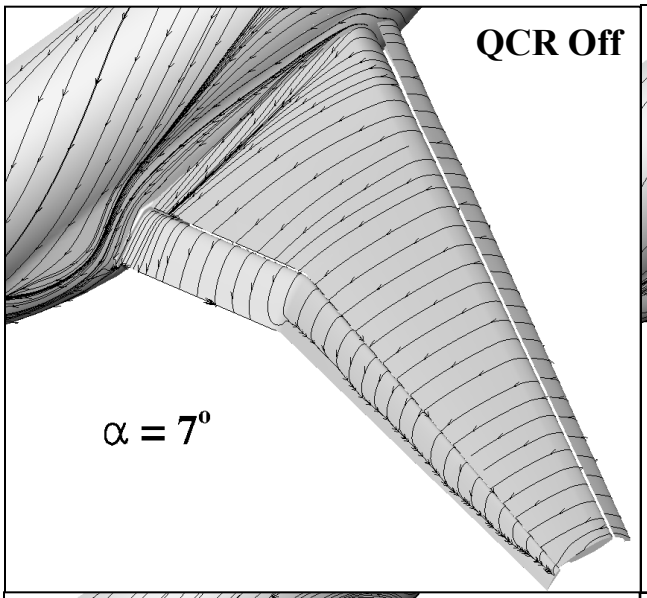
CFD High Lift Prediction Workshop

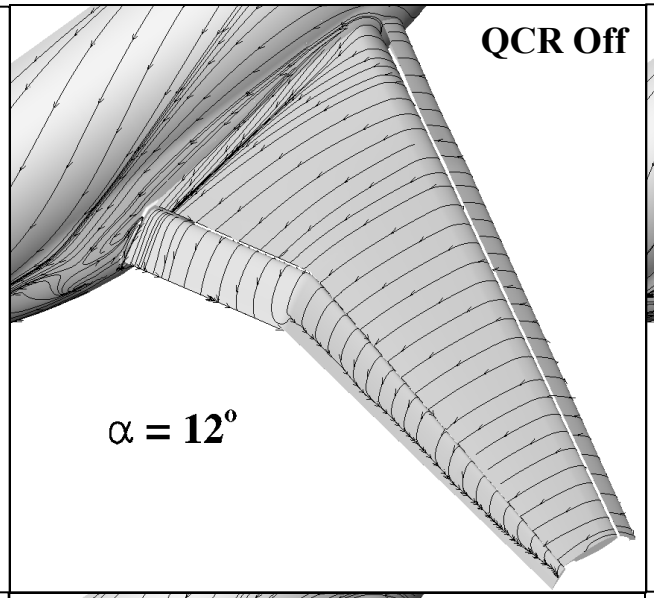


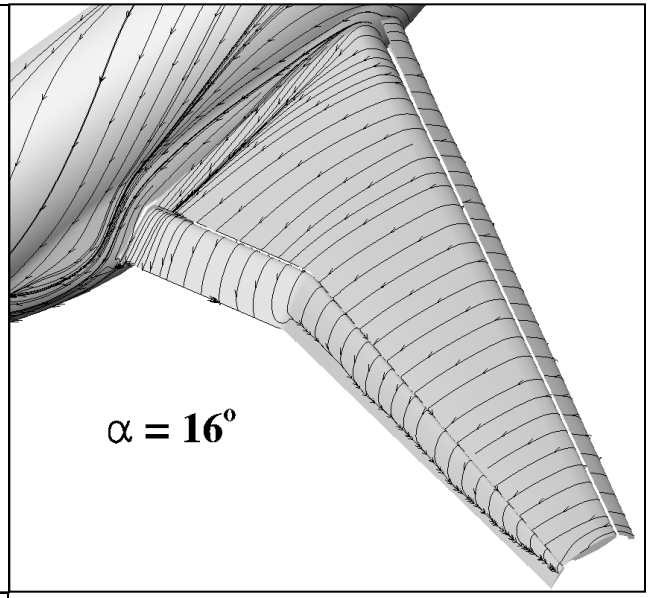


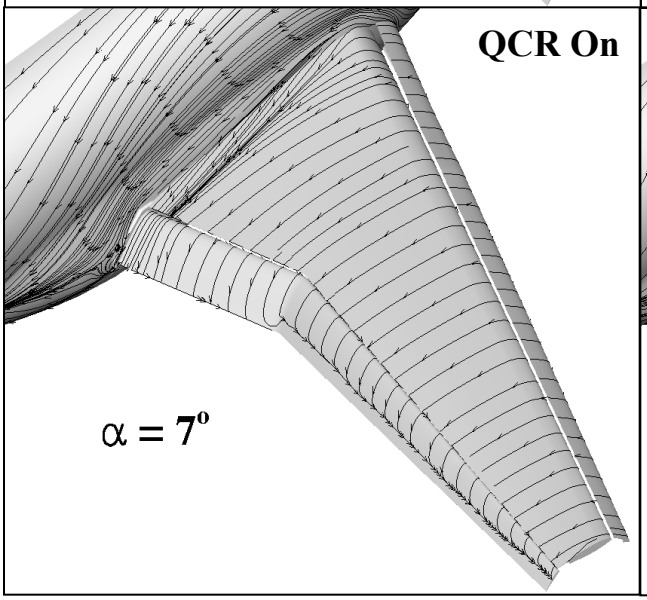
Test Case 1 – Grid Convergence Study

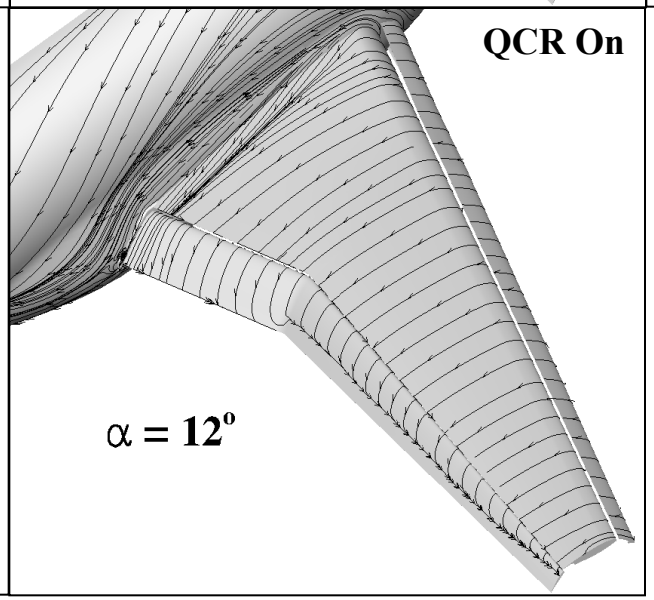
Brackets/Fairings-Off Surface Streamlines: COARSE





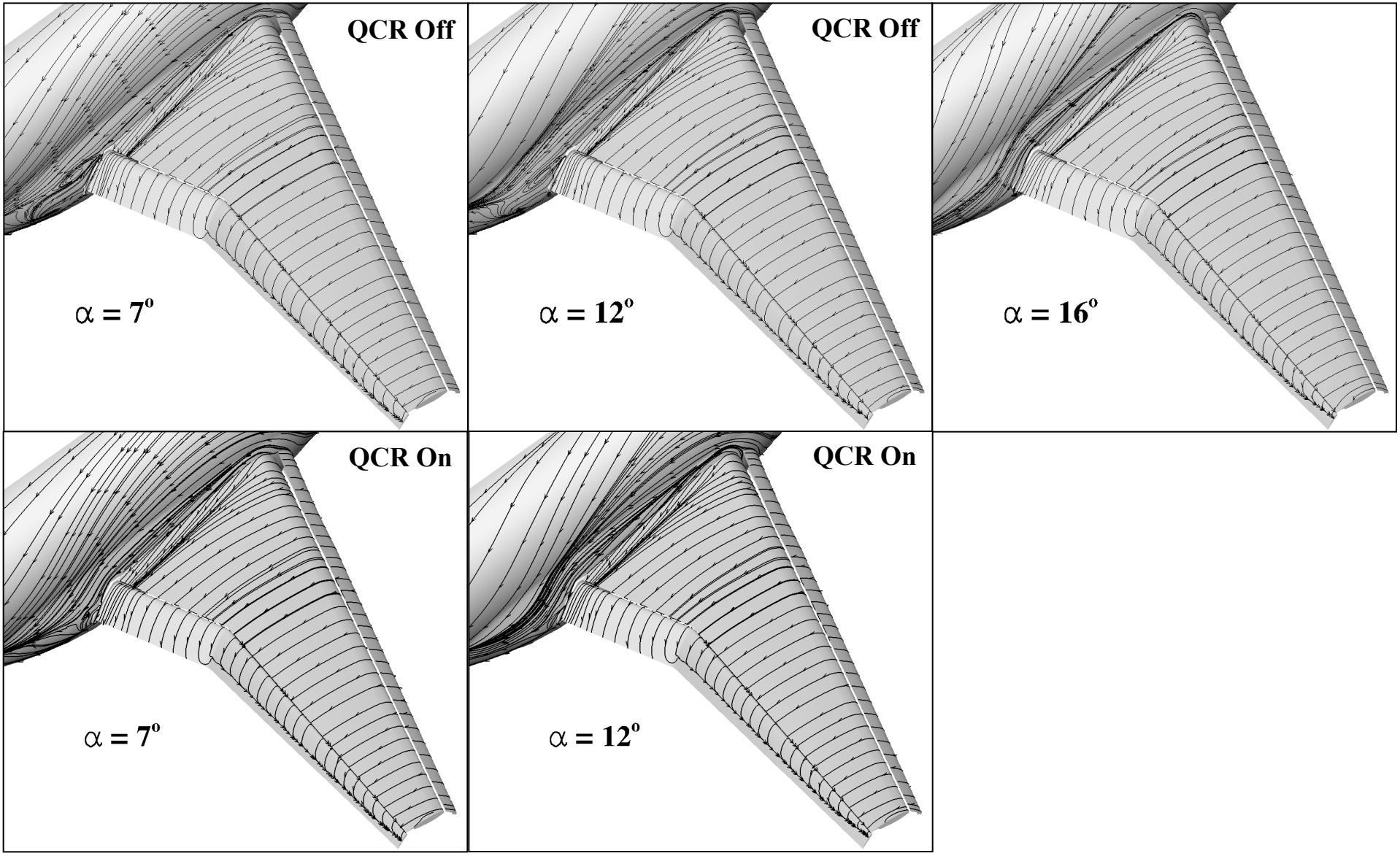






Test Case 1 – Grid Convergence Study

Brackets/Fairings-Off Surface Streamlines: MEDIUM



Test Case 1 – Grid Convergence Study

Brackets/Fairings-Off Surface Streamlines: FINE

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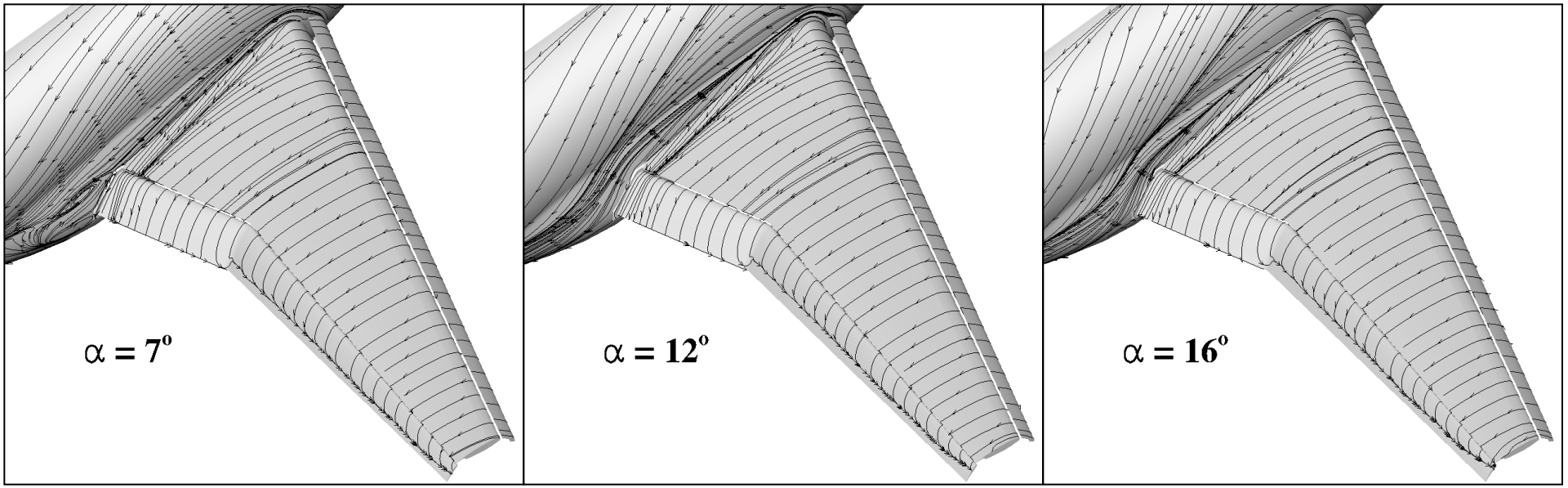

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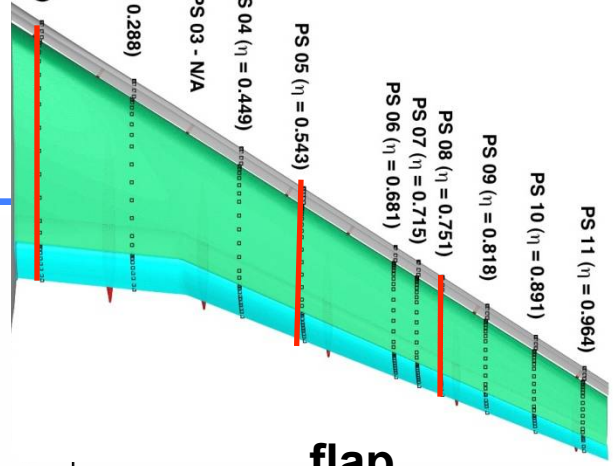
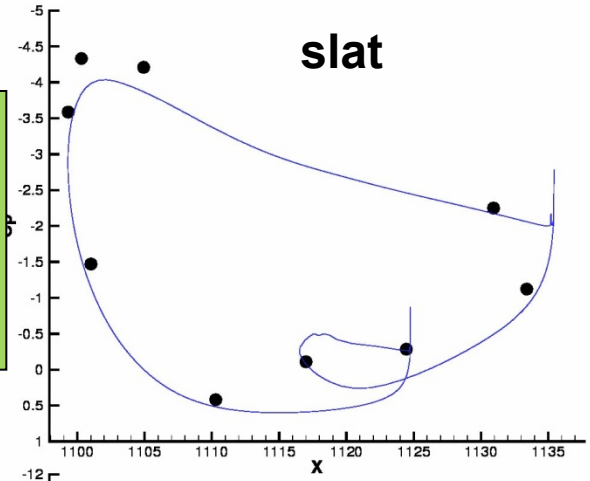
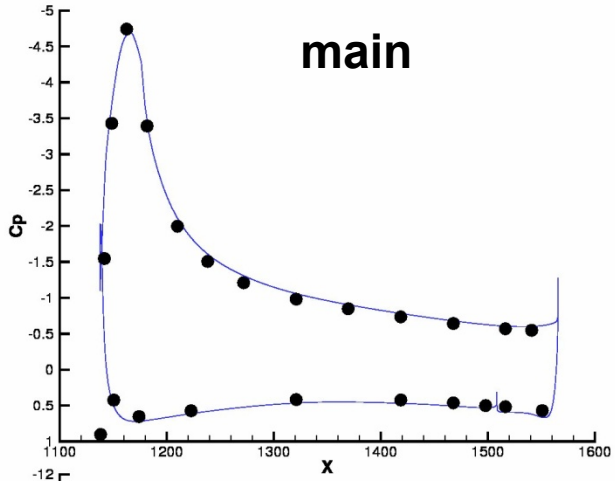
Test Case 2a – Reynolds Number Study

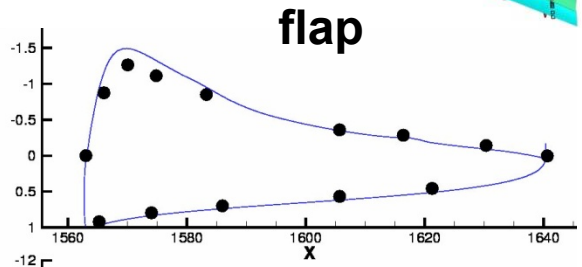
Brackets / Fairings On, QCR On, α = 20°



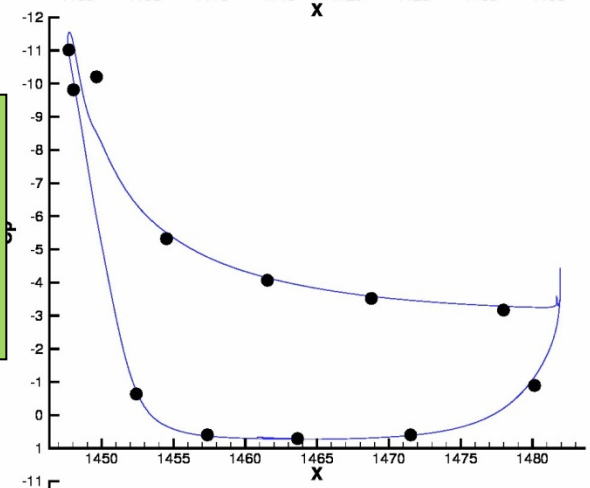
η = 0.150

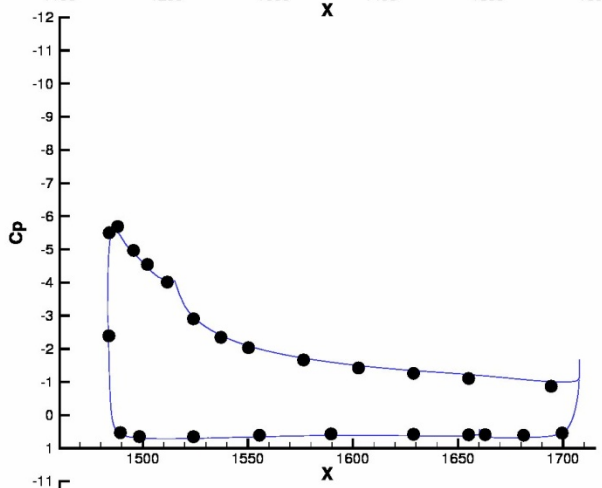


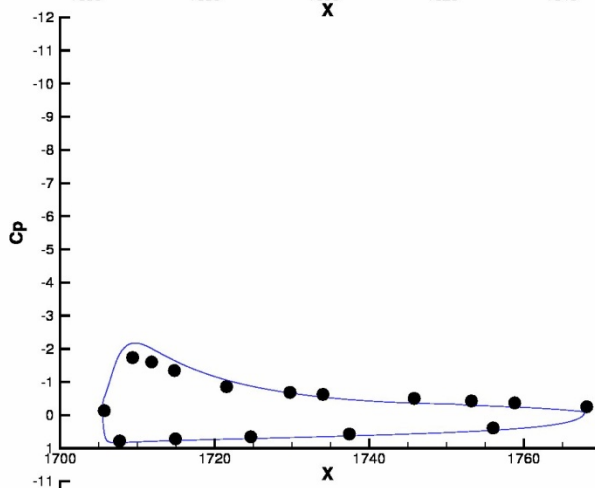




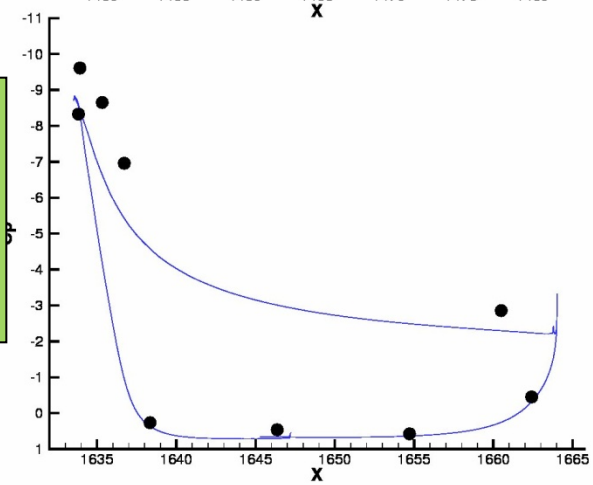
η = 0.543

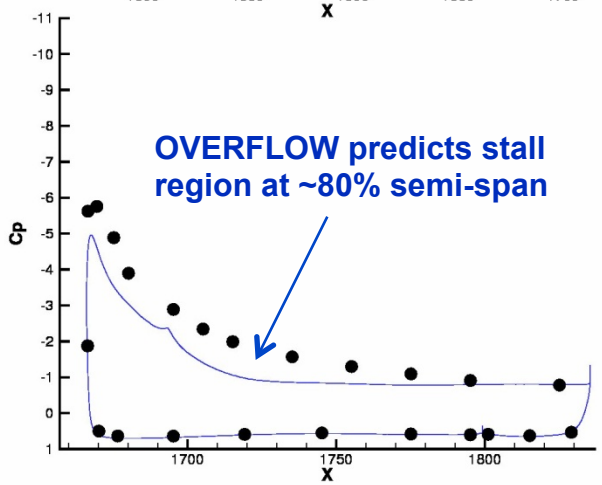


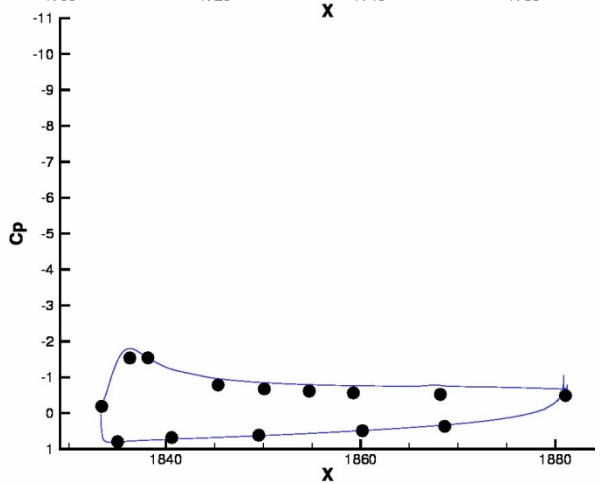




η = 0.751







Convergence History

Case 1 C_L – Low Alpha Side-of-Body Flow Field

CFD High Lift Prediction Workshop

F11 Config 2: Slat Brackets / Flap Fairings Off

Mach = 0.175, Reynolds number = 15.1 million

Fully Turbulent, Free Air

Medium Grid, α = 7°